
Capillary Two-Phase Thermal Devices - An Introduction

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Outline

- **Introduction/Overview**
 - **Heat Pipes**
 - **Capillary Pumped Loops**
 - **Loop Heat Pipes**
 - **Summary**
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- ** Thermal Devices**
 - **Hardware Construction**
 - **Operating Principles**
 - **Performance Characteristics**
 - **Applications**
 - **Current Development**

Disclaimer

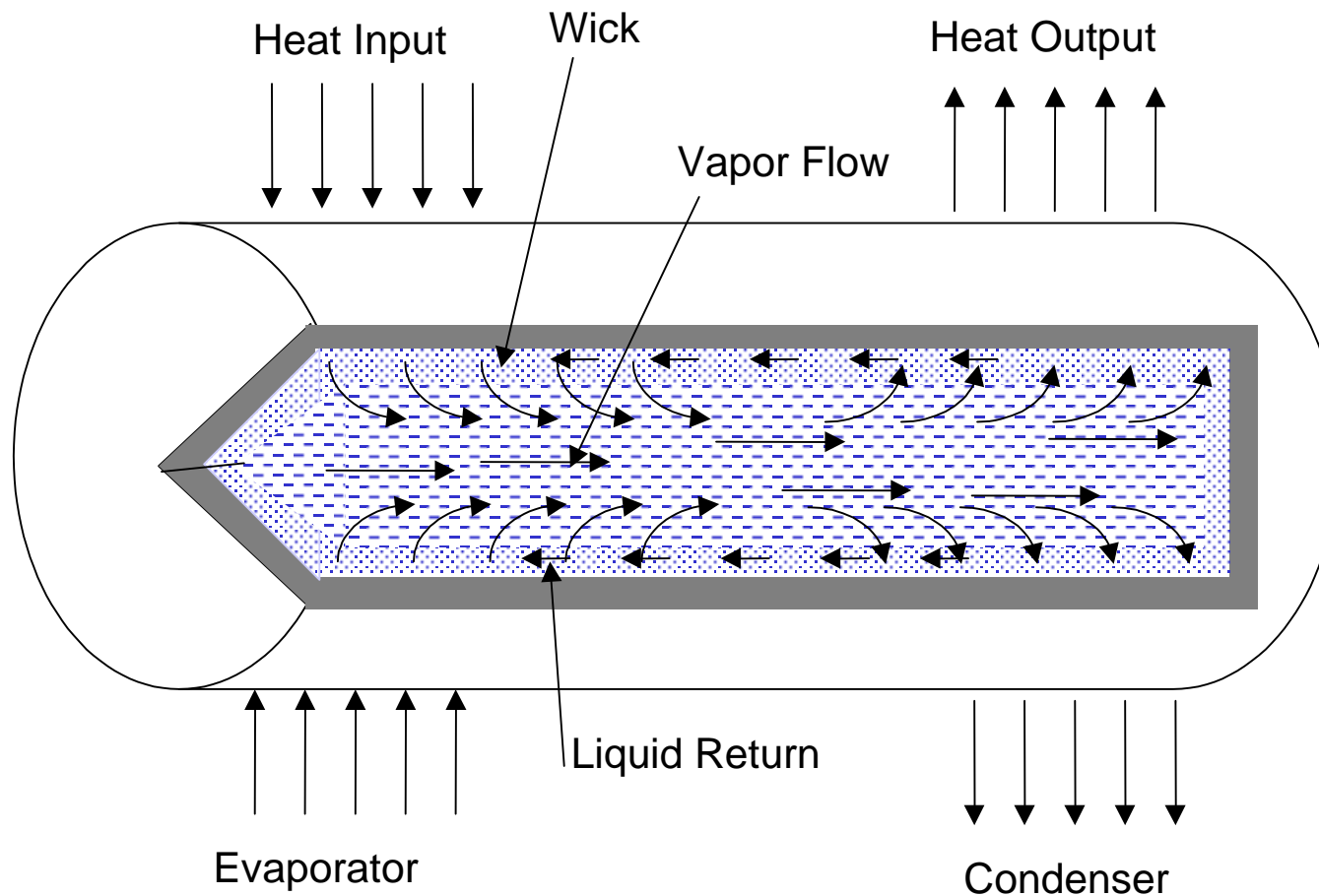
Note:

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Introduction

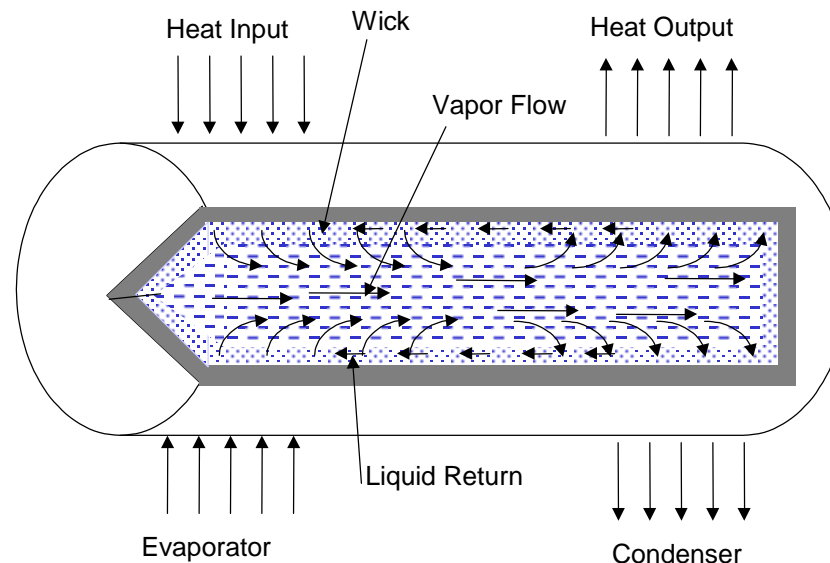
- **Why Capillary Two-Phase Devices?**
 - **Two-phase capillary devices can transfer large heat loads over long distances with small temperature differences.**
- **Existing Capillary Two-Phase Devices**
 - **Heat Pipe**
 - **Capillary Pumped Loop**
 - **Loop Heat Pipe**

Schematic of a Heat Pipe



Operating Principles of Capillary Two-Phase Devices

- Waste heat is absorbed by the working fluid through evaporation, transported to the heat sink, and dissipated through condensation.
- The capillary force developed at the liquid and vapor interface in the fine porous wick circulates the fluid.
 - The waste heat serves as the ultimate driving force.
- The capillary pressure will self adjust so that it is equal to the total pressure drop in the loop at all times.
- When the total pressure drop is equal to the maximum capillary pressure that the wick can sustain, the maximum heat transport capability is reached.



Pressure Balance in Capillary Two-Phase Devices

- As the liquid is vaporizing, a meniscus is formed at the liquid/vapor interface in the wick, and a capillary pressure is developed across the meniscus.

$$\Delta P_{\text{cap}} = 2\sigma \cos\theta/R$$

- The total pressure drop is the sum of pressure drops in various components.

$$\Delta P_{\text{tot}} = \Delta P_{\text{evap}} + \Delta P_{\text{vap}} + \Delta P_{\text{cond}} + \Delta P_{\text{liq}} + \Delta P_{\text{g}}$$

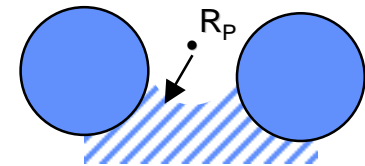
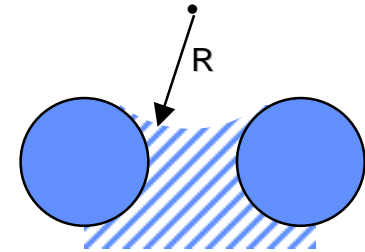
- The meniscus will curve naturally so the the capillary pressure is equal to the total pressure drop.

$$\Delta P_{\text{cap}} = \Delta P_{\text{tot}}$$

- The maximum capillary pressure that the wick can develop can be expressed as

$$\Delta P_{\text{cap,max}} = 2\sigma \cos\theta/R_p$$

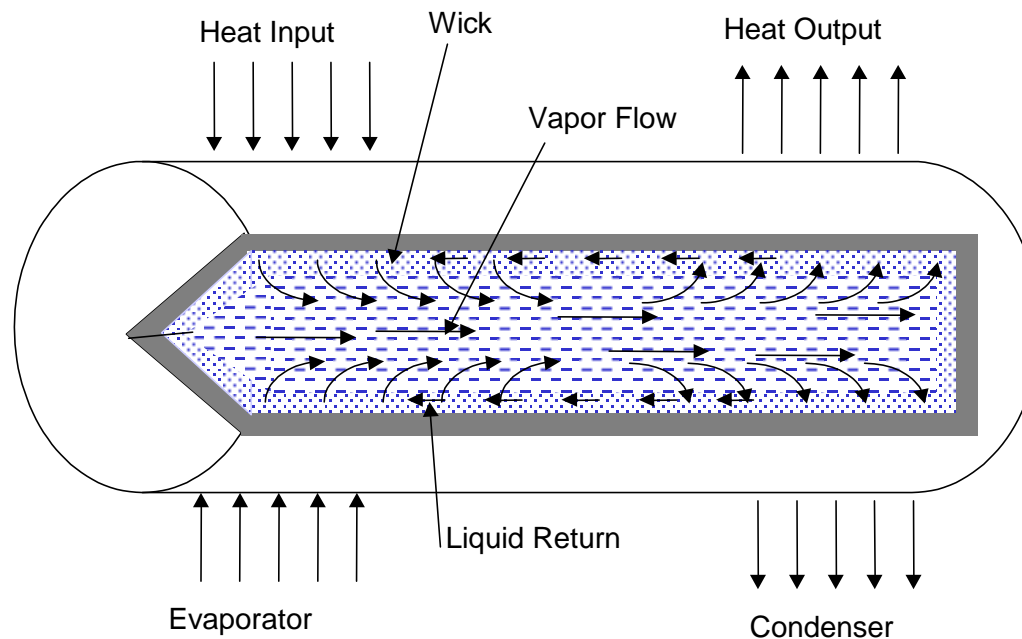
$$R \geq R_p$$



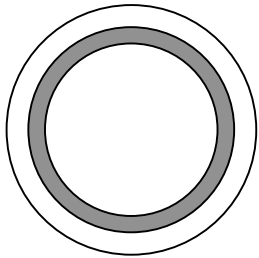
Heat Pipes

Functional Types Of Heat Pipes

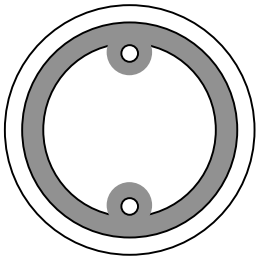
- **Three Basic Functional Types**
 - **Constant Conductance Heat Pipe (CCHP)**
 - **Variable Conductance Heat Pipe (VCHP)**
 - **Diode Heat Pipe**
- **Many Hardware Variations Exist.**
 - **Diameter**
 - **Length**
 - **Shape**
 - **Wick Material**
 - **Wick Construction**
 - **Working Fluid**



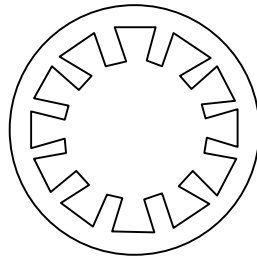
Some Wicks Used in Heat Pipes



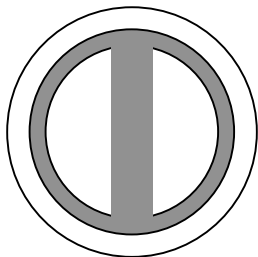
CIRCUMFERENTIAL
SCREEN WICK



POWDER METAL WITH
PEDESTAL ARTERY



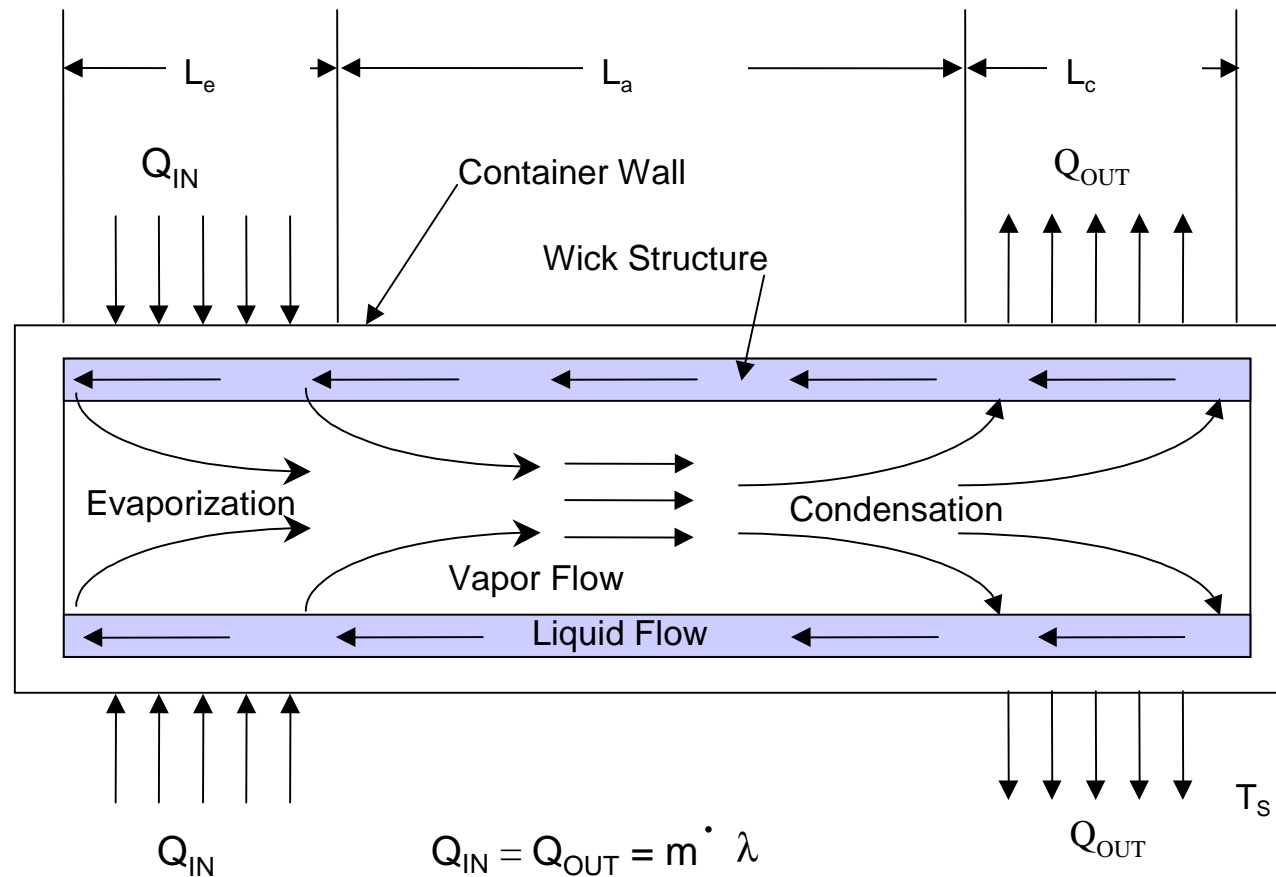
AXIAL GROOVES



SLAB WICK



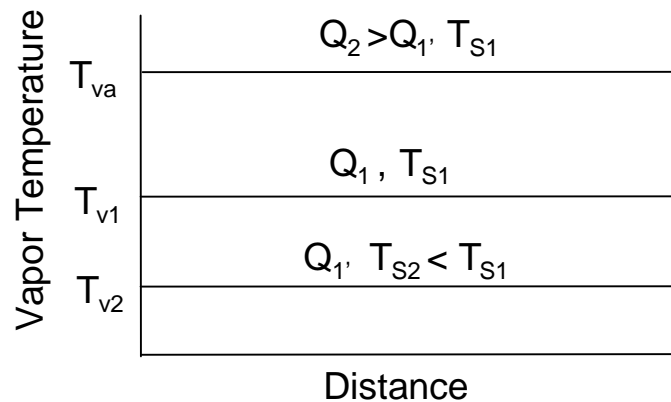
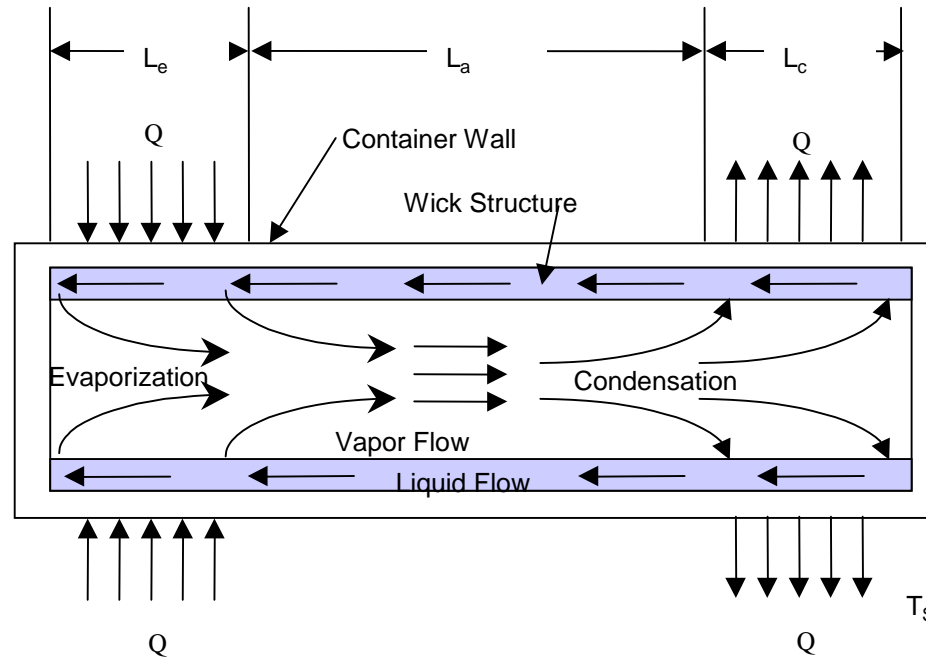
Energy Balance in Heat Pipe



$$Q_{IN} = Q_{OUT} = \dot{m} \cdot \lambda$$

L_e = Evaporator length
 L_a = Adiabatic length
 L_c = Condenser length
 \dot{m} = Mass flow rate (liquid or vapor)
 λ = Latent heat of vaporization

Constant Conductance Heat Pipe

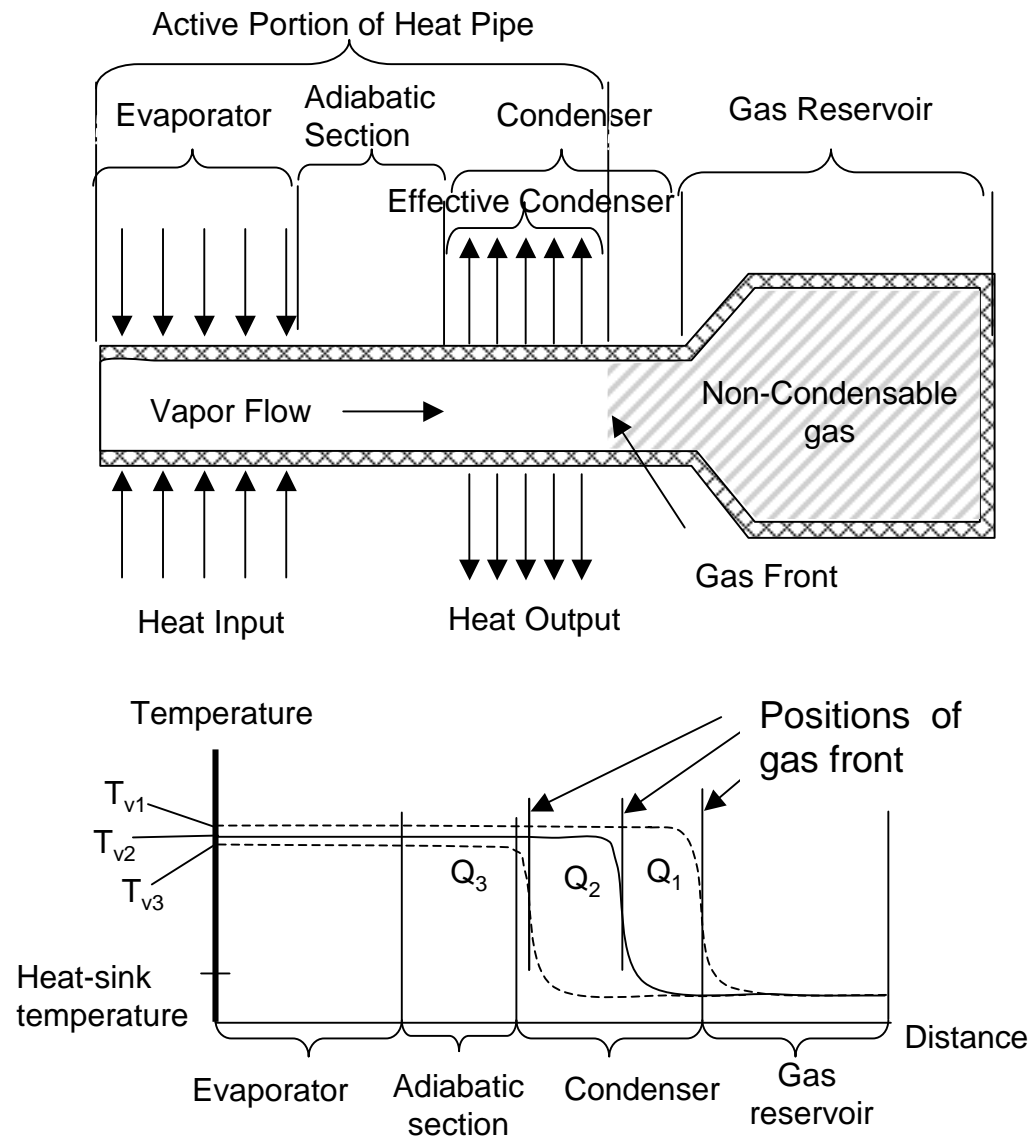


$$Q = h(\pi D L_c)(T_v - T_s)$$

$$L_c = \text{Constant}$$

T varies with T_s and/or Q

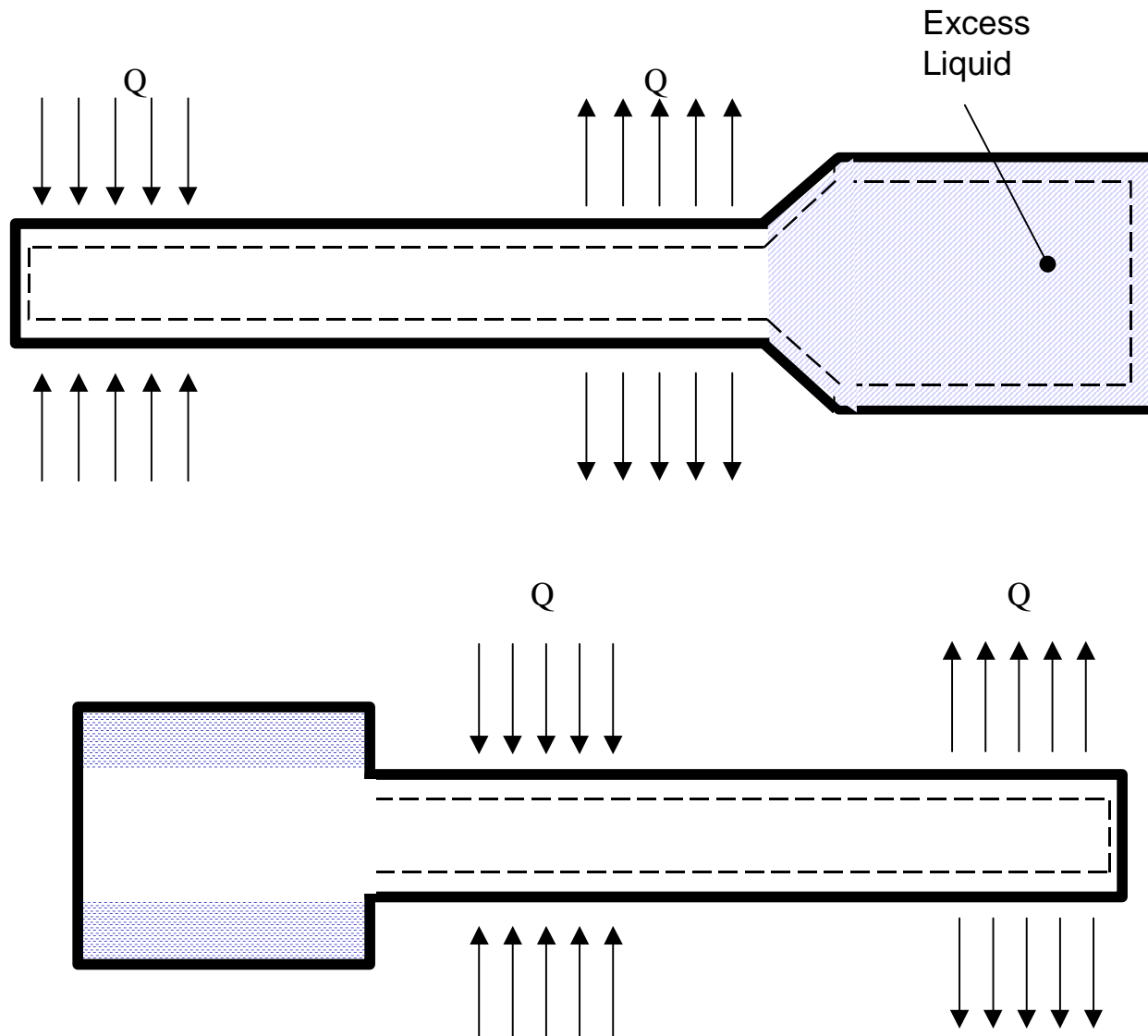
Thermal Characteristics of a VCHP



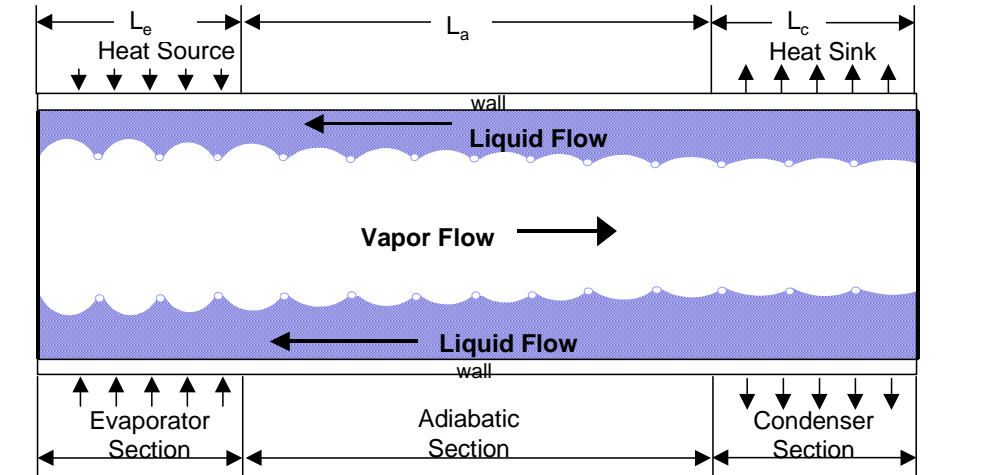
$$Q = h(\pi D L_c)(T_v - T_s)$$

L_c varies with T_s and/or Q
so as to keep T_v constant

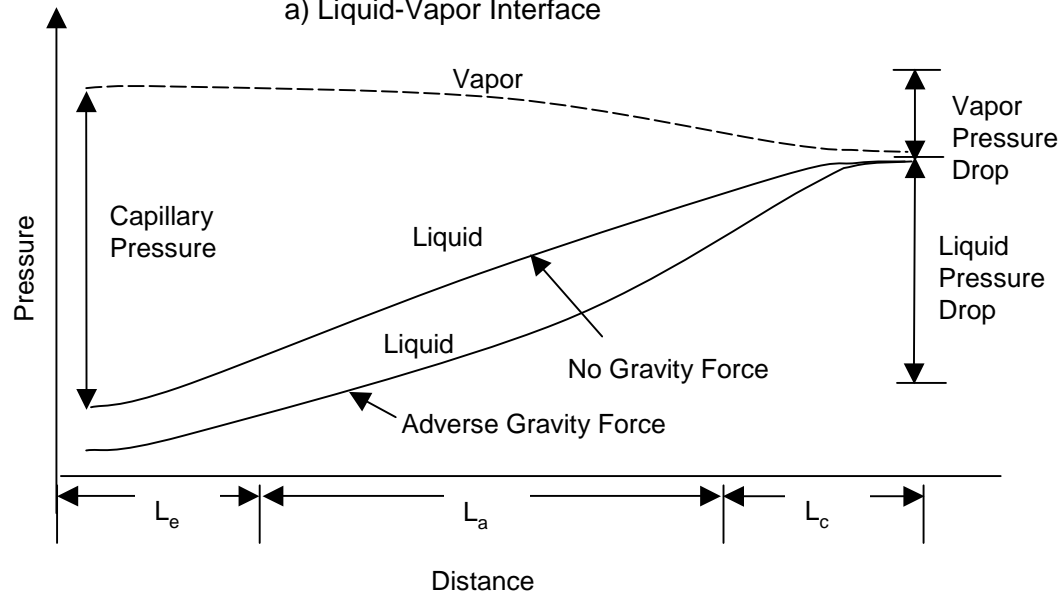
Diode Heat Pipes



Pressure Drop Diagram of a Heat Pipe



a) Liquid-Vapor Interface



b) Vapor and liquid pressure distributions

- **Heat Transport Limit**

$$(QL)_{\max} = QL_{\text{eff}}$$

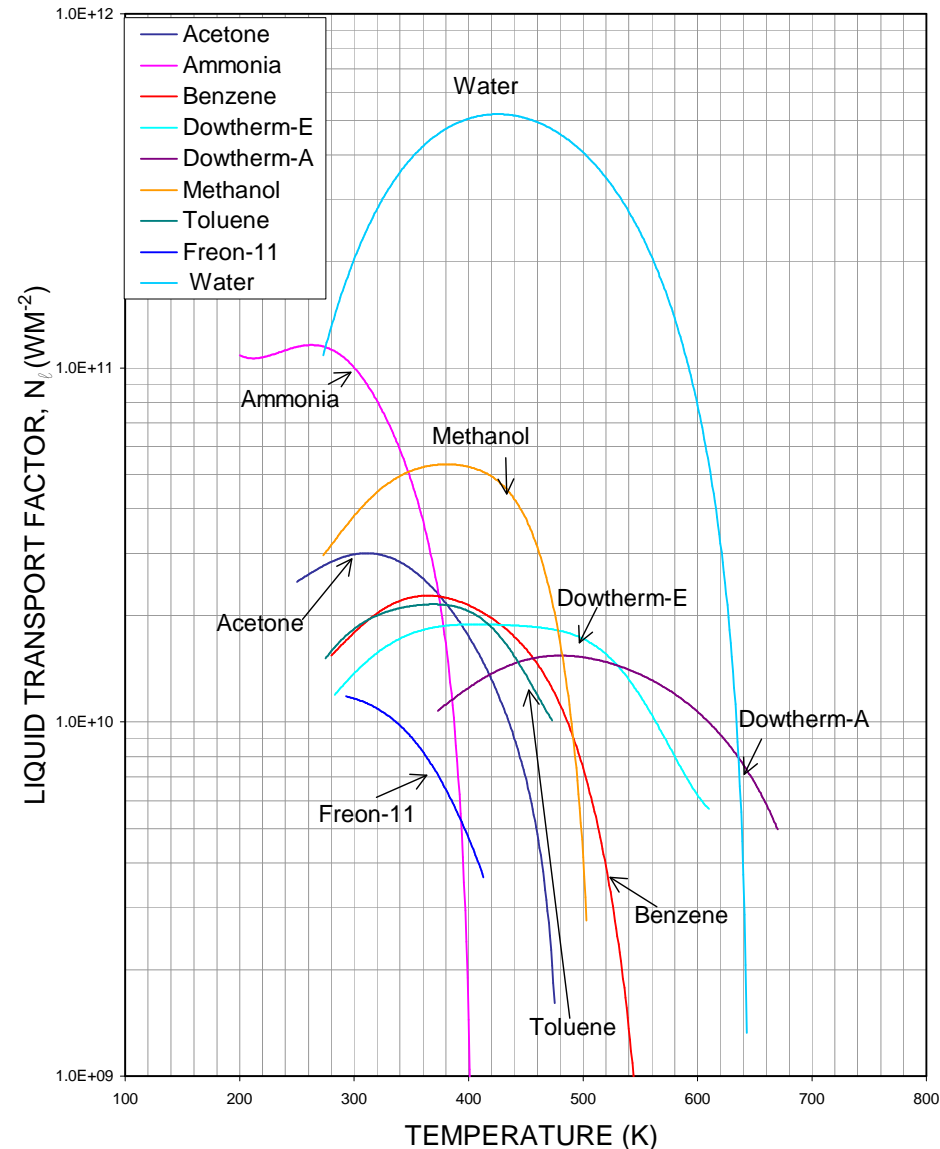
$$L_{\text{eff}} = 0.5 L_e + L_a + 0.5 L_c$$

**$(QL)_{\max}$ in Watt-Inches
or Watt-Meters**

Liquid Transport Factor vs Temperature

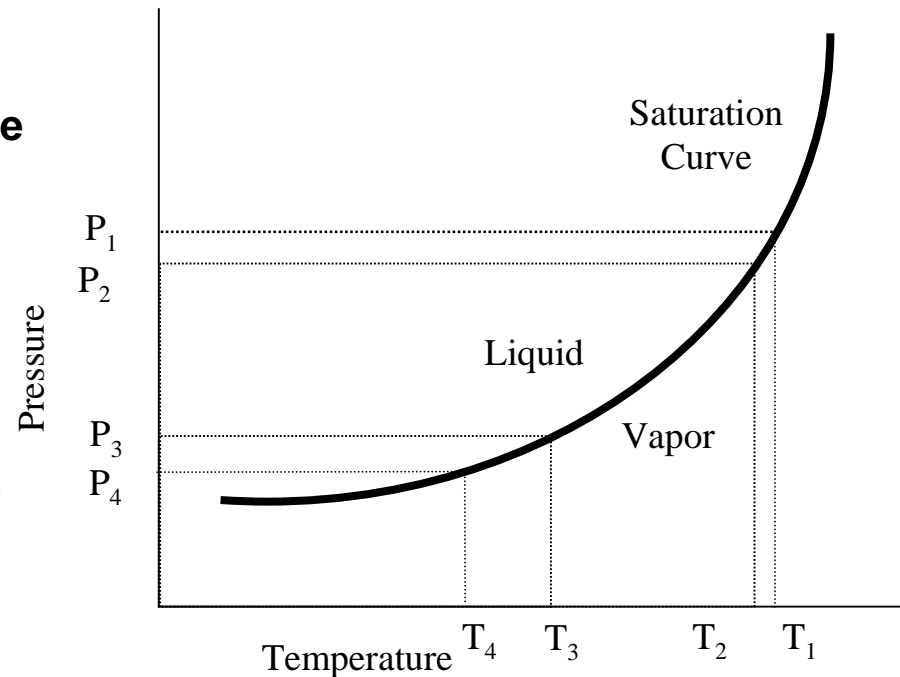
- Convenient figure of merit is liquid transport factor, N_l ,

$N_l = \text{latent heat} * \text{surface tension} * \text{density} / \text{viscosity}$

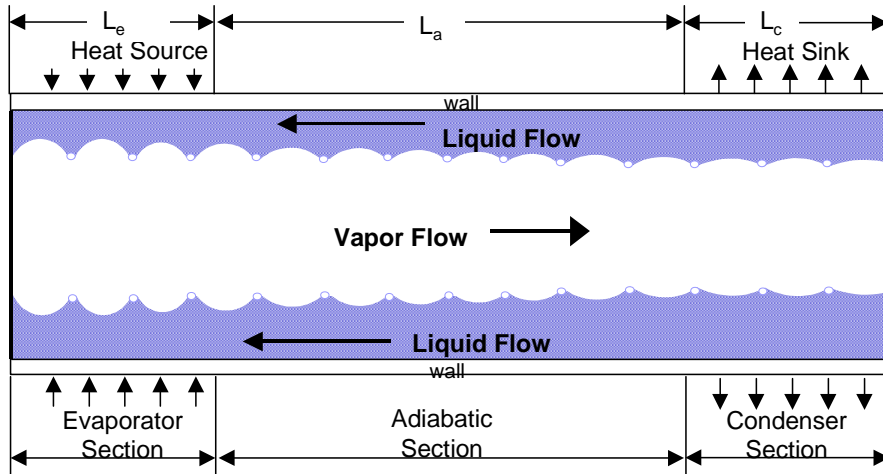


Heat Pipe Design Considerations

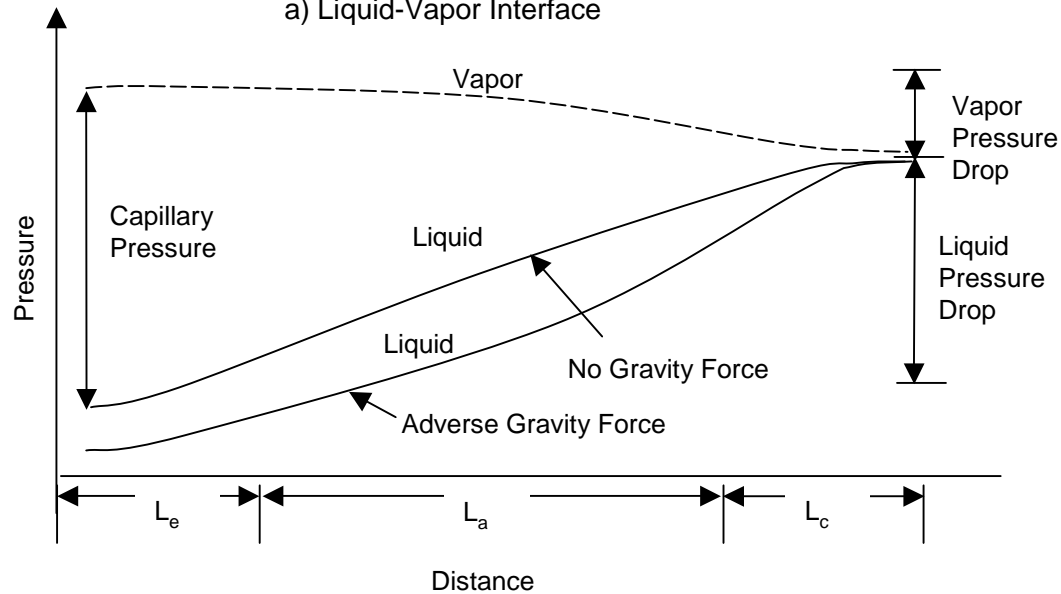
- Determine the operating temperature range.
- Select the working fluid
 - Liquid transport factor
 - Never operate near the freezing temperature or the critical temperature of the working fluid.
- Select the container material.
 - Material compatibility
- Select the wick.
 - Material
- From the thermal requirement, determine the type of heat pipe.
 - CCHP, VCHP, Diode HP
- From the heat transport requirement, determine the heat pipe diameter and length, and number of heat pipes.
 - Temperature drop across the heat pipe
 - Temperature gradient requirement
 - Some computer models available



Pressure Drop Diagram of a Heat Pipe



a) Liquid-Vapor Interface



b) Vapor and liquid pressure distributions

- Heat Transport Limit

$$(QL)_{\max} = QL_{\text{eff}}$$

$$L_{\text{eff}} = 0.5 L_e + L_a + 0.5 L_c$$

- Capillary pressure head:

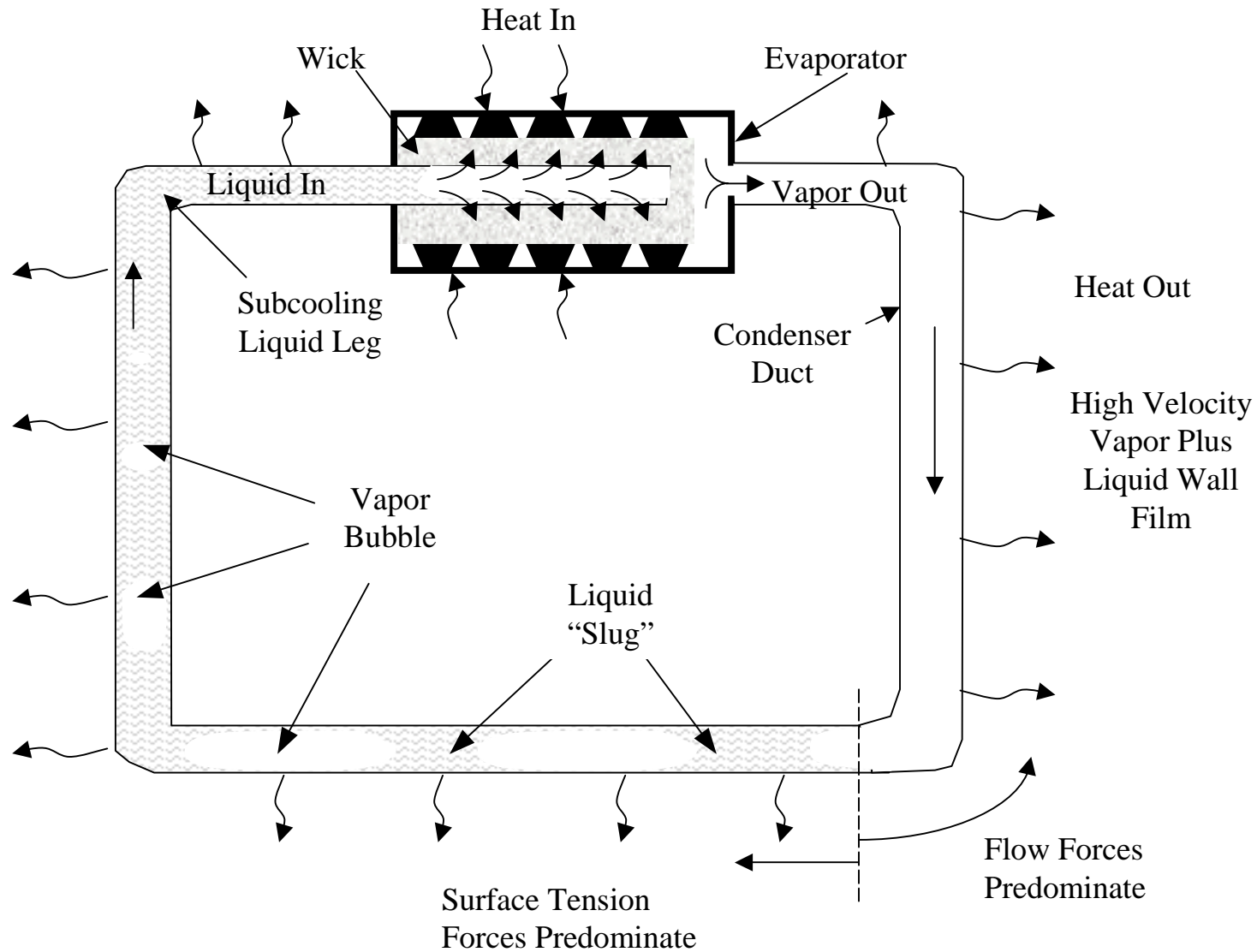
$$\Delta P_{\text{cap}} \propto 1/r$$

- Liquid pressure drop:

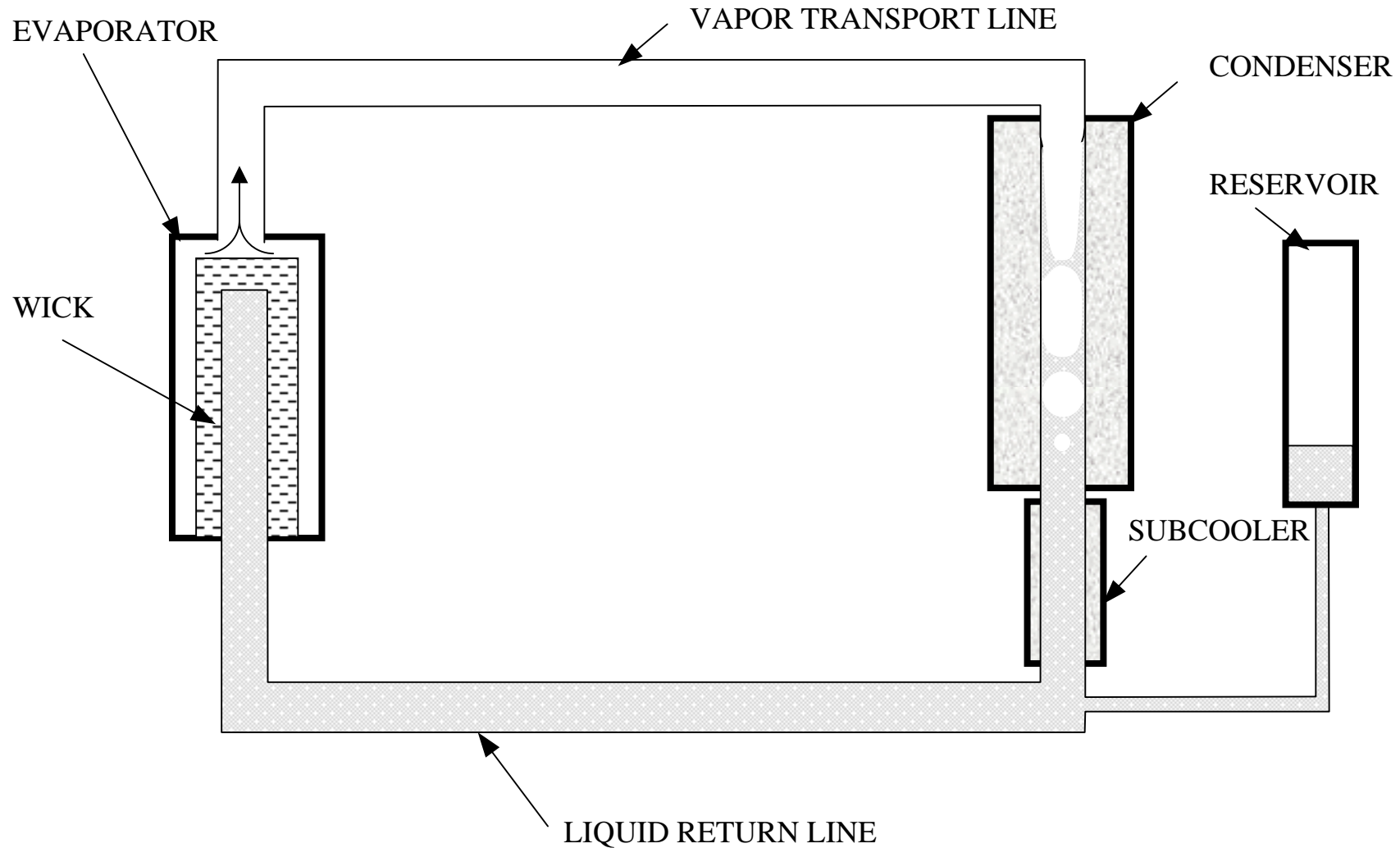
$$\Delta P_{\text{liq}} \propto 1/r^2$$

Capillary Pumped Loops

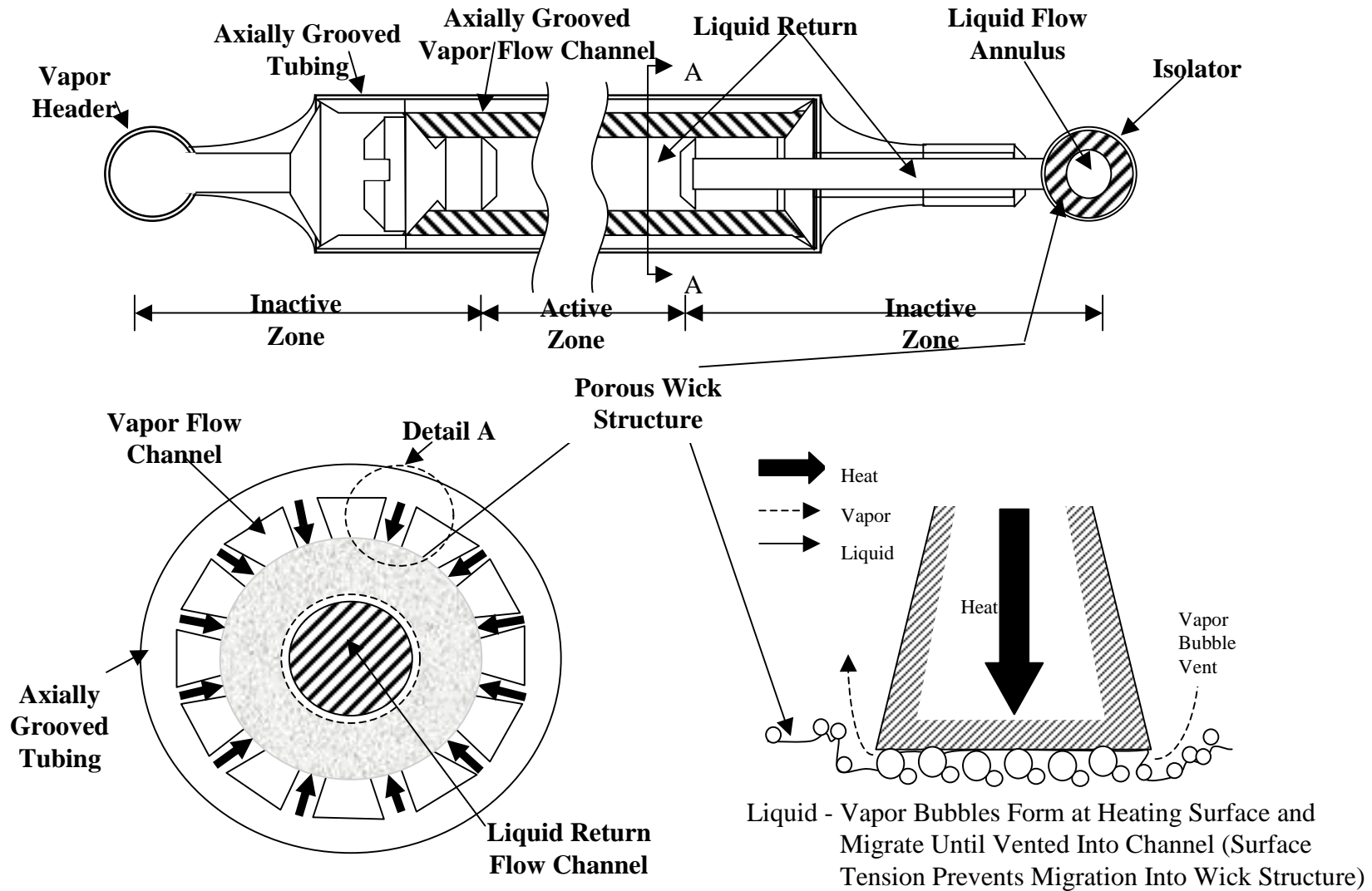
Schematic of a Constant Conductance CPL



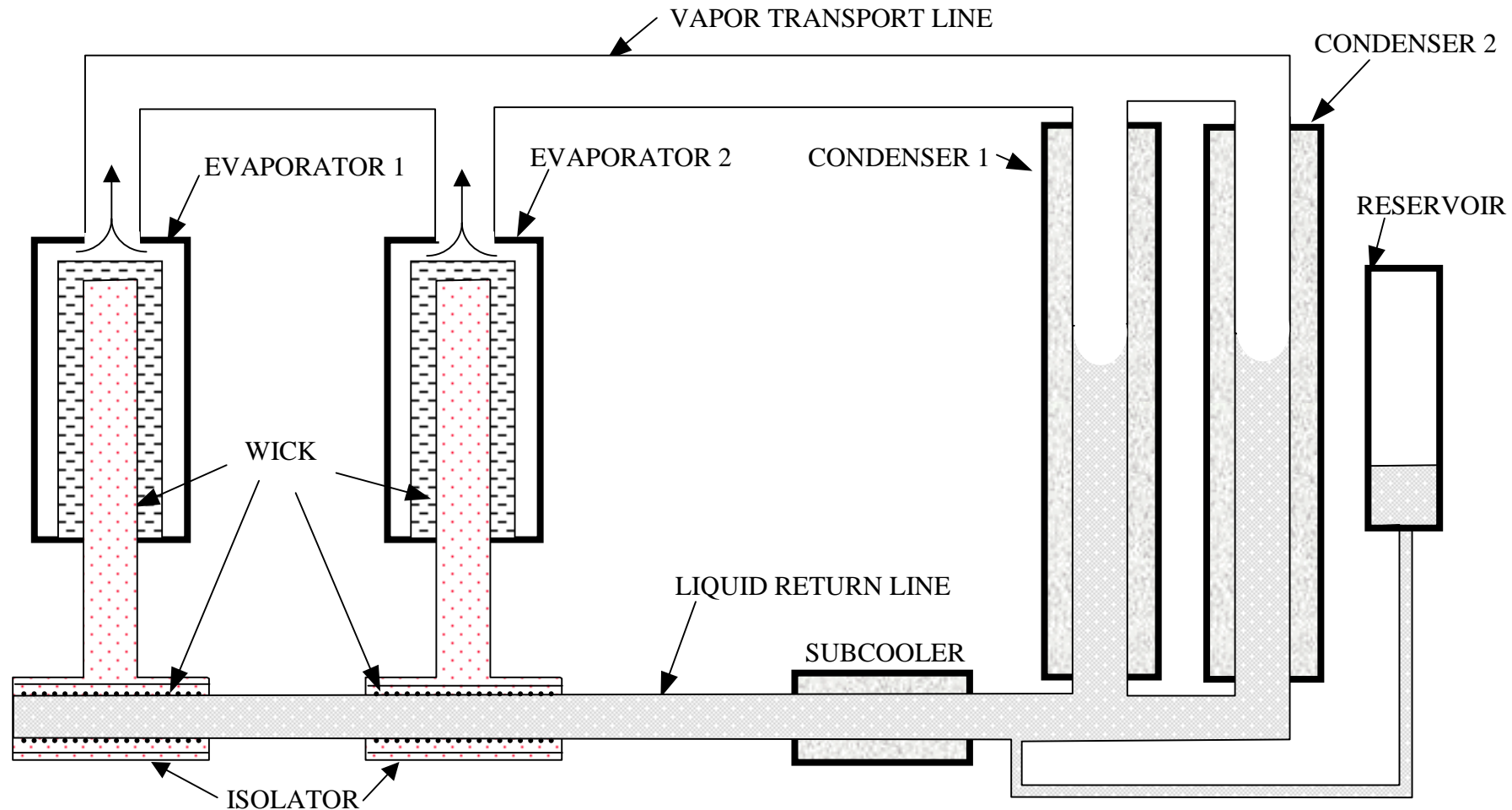
Schematic of a Variable Conductance CPL



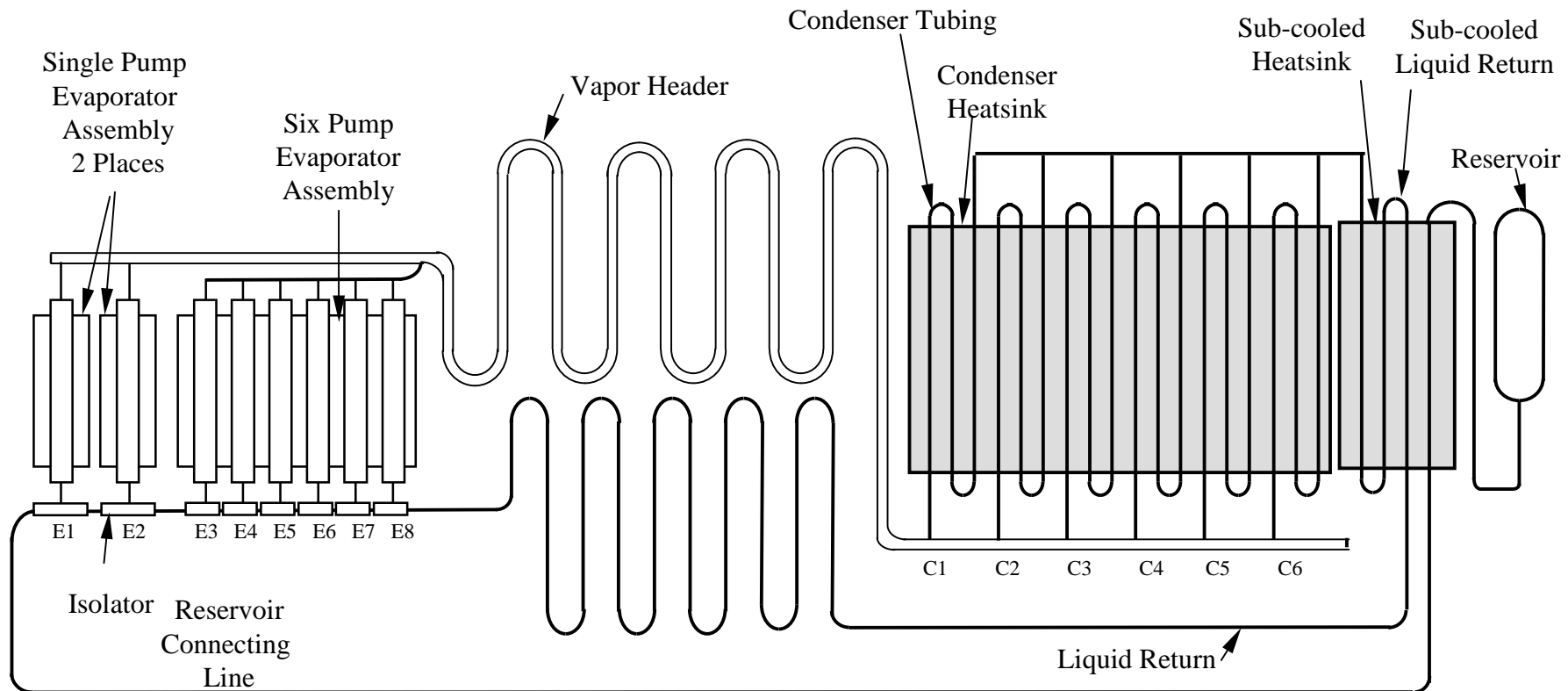
Capillary Evaporator Pump



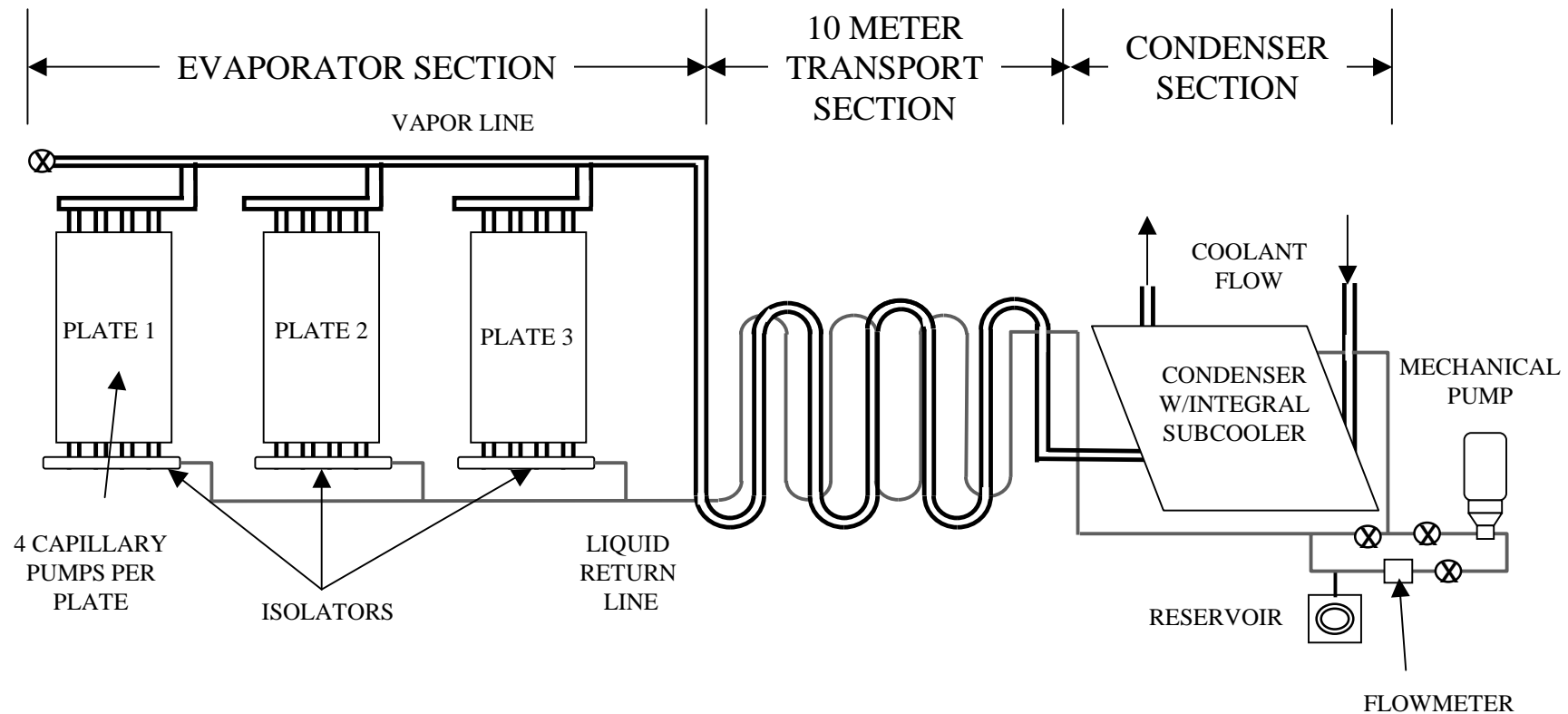
Schematic of a CPL with Multiple Evaporators and Multiple Condensers



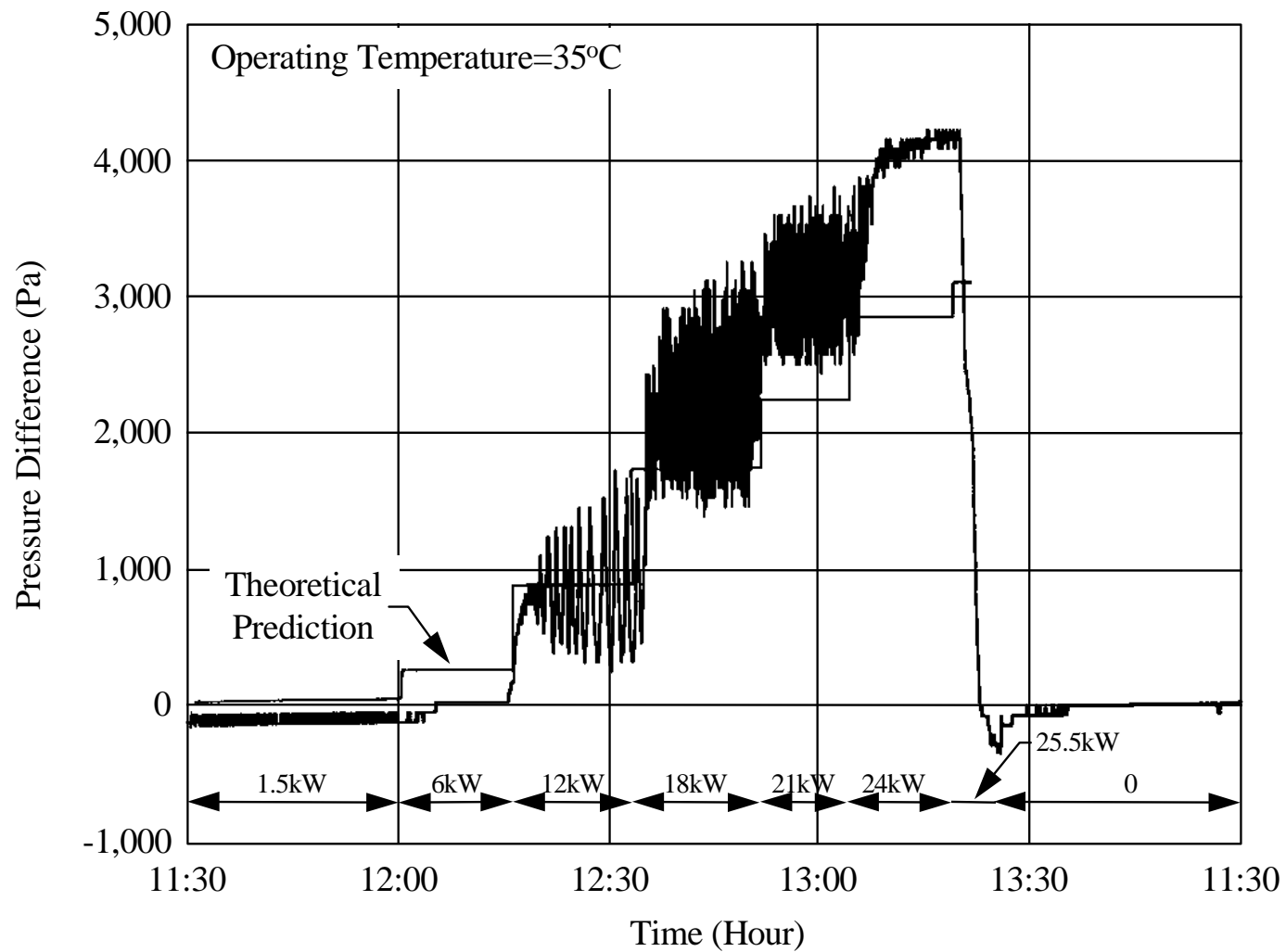
Schematic of CPL 1



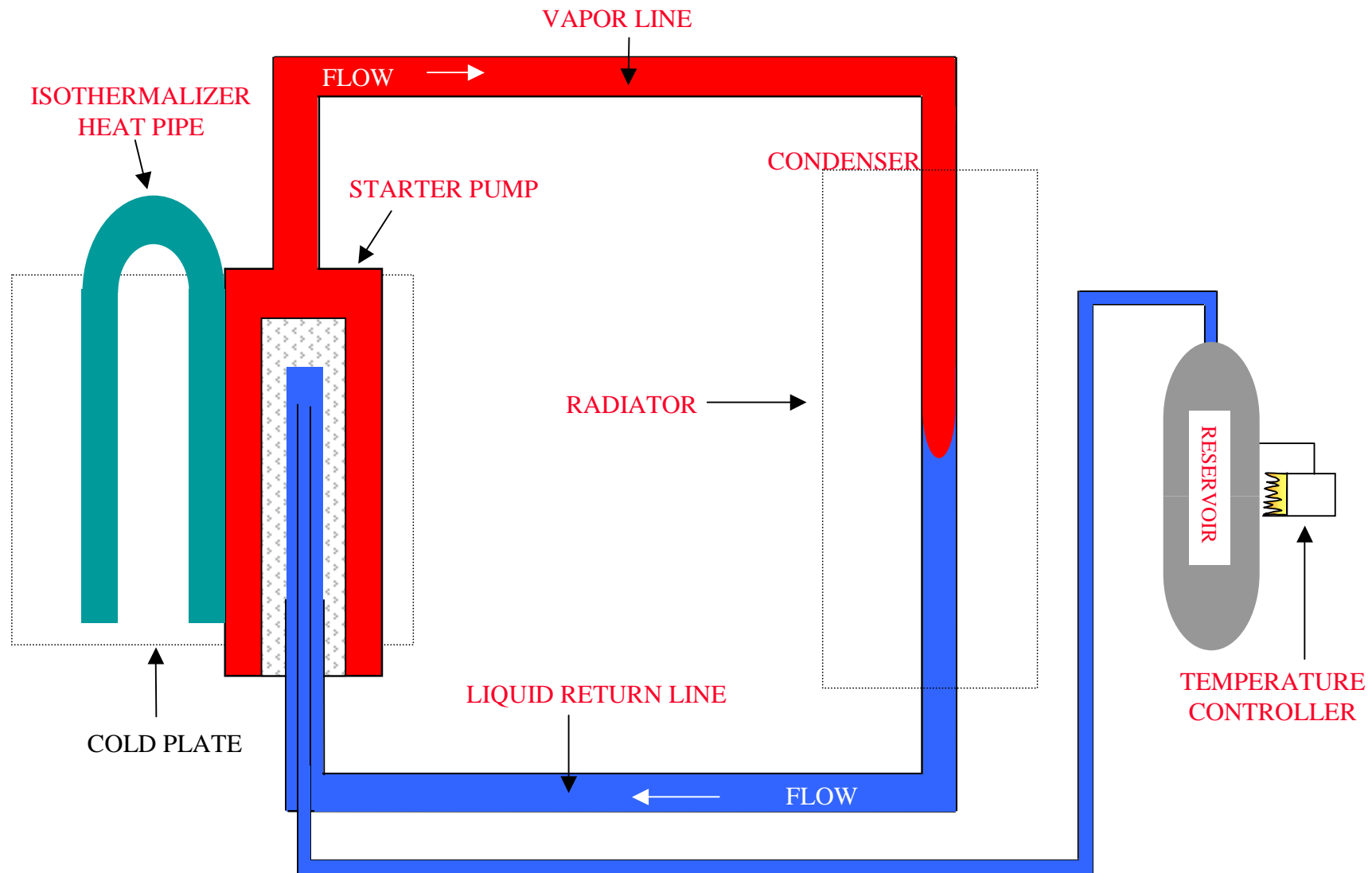
Schematic of HPSTM Demonstration System



HPSTM Thermal Performance

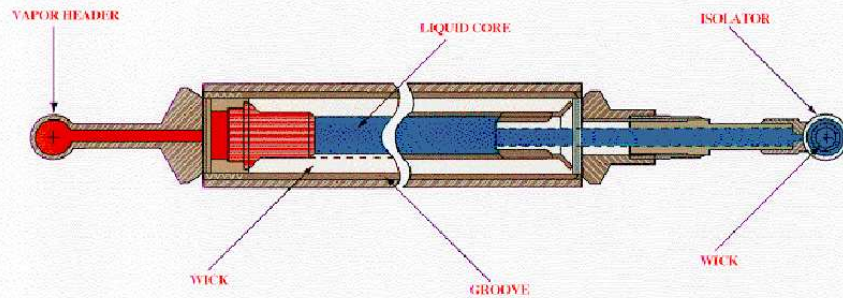


EOS-TERRA CPL Flow Schematic

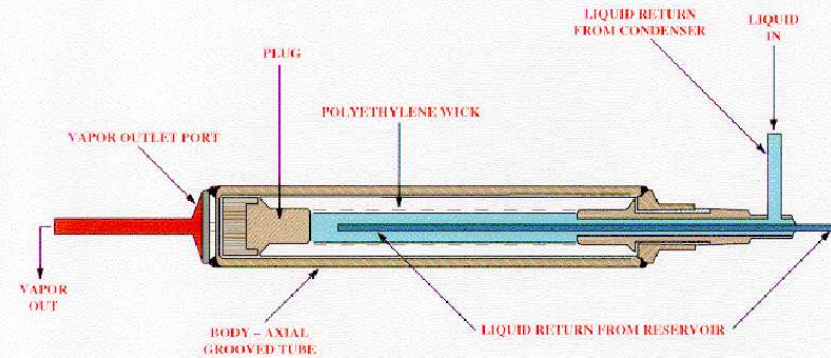


Two Evaporator Designs

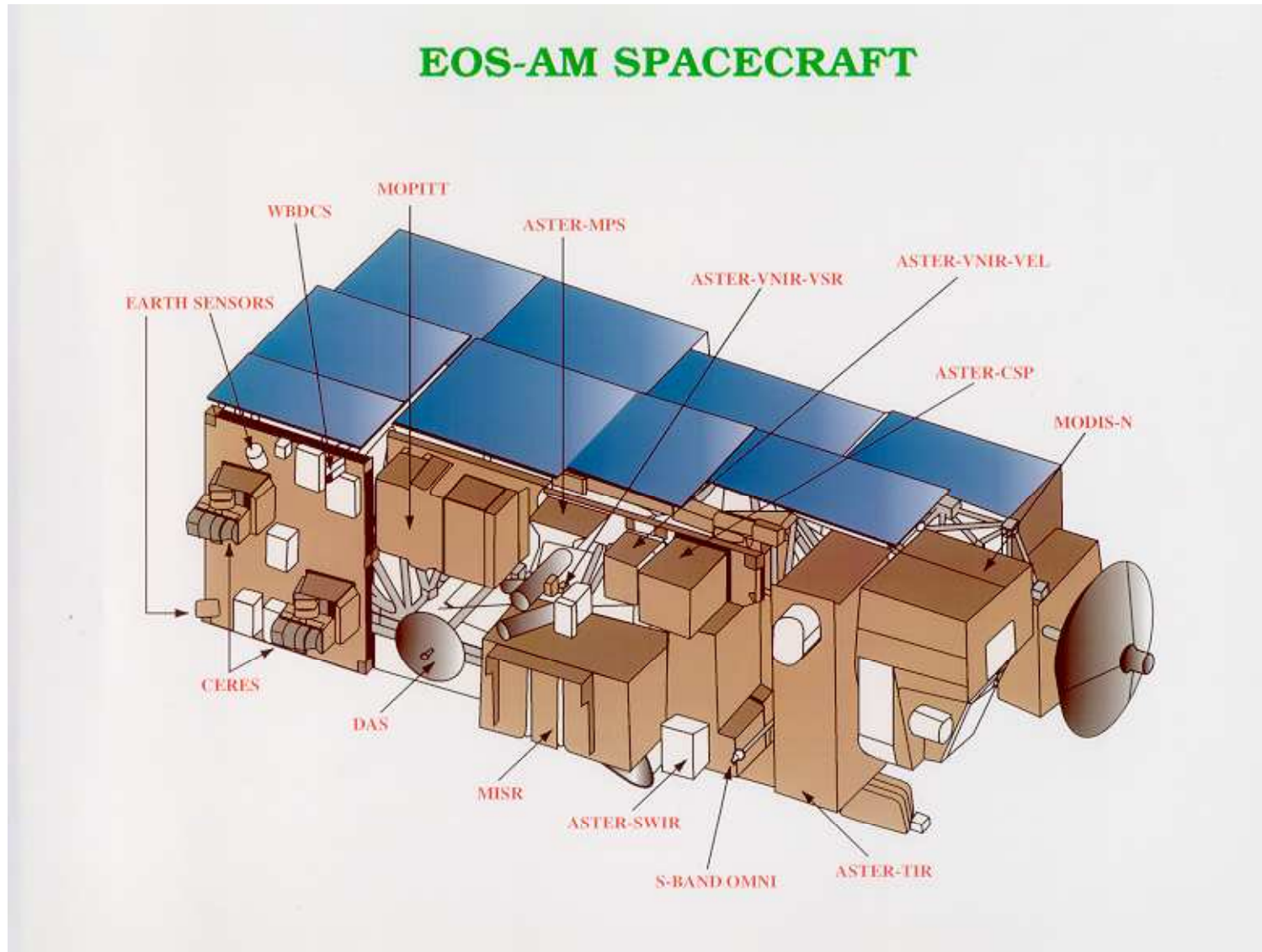
TRADITIONAL CAPILLARY PUMP



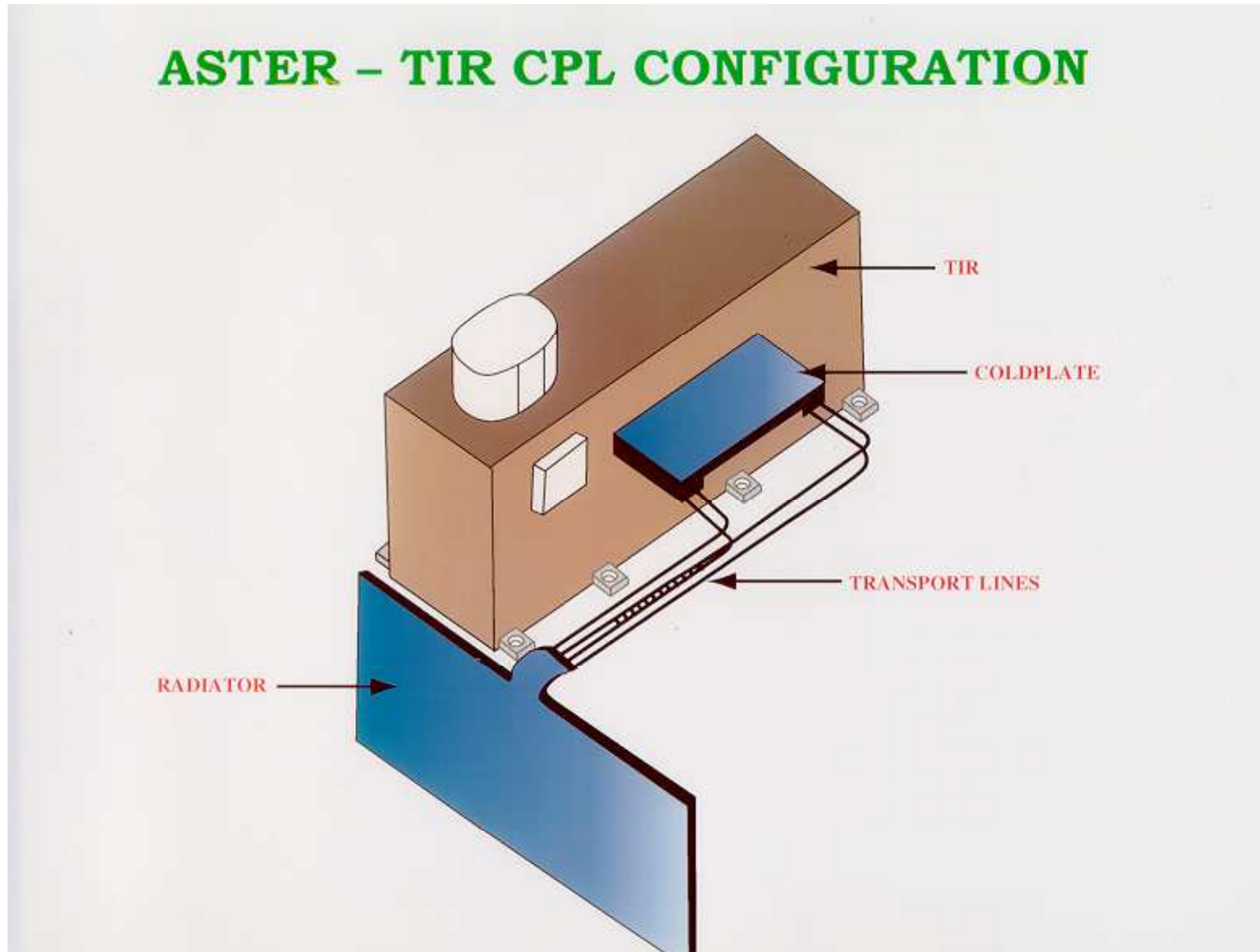
SCHEMATIC OF STARTER PUMP



EOS - TERRA Spacecraft

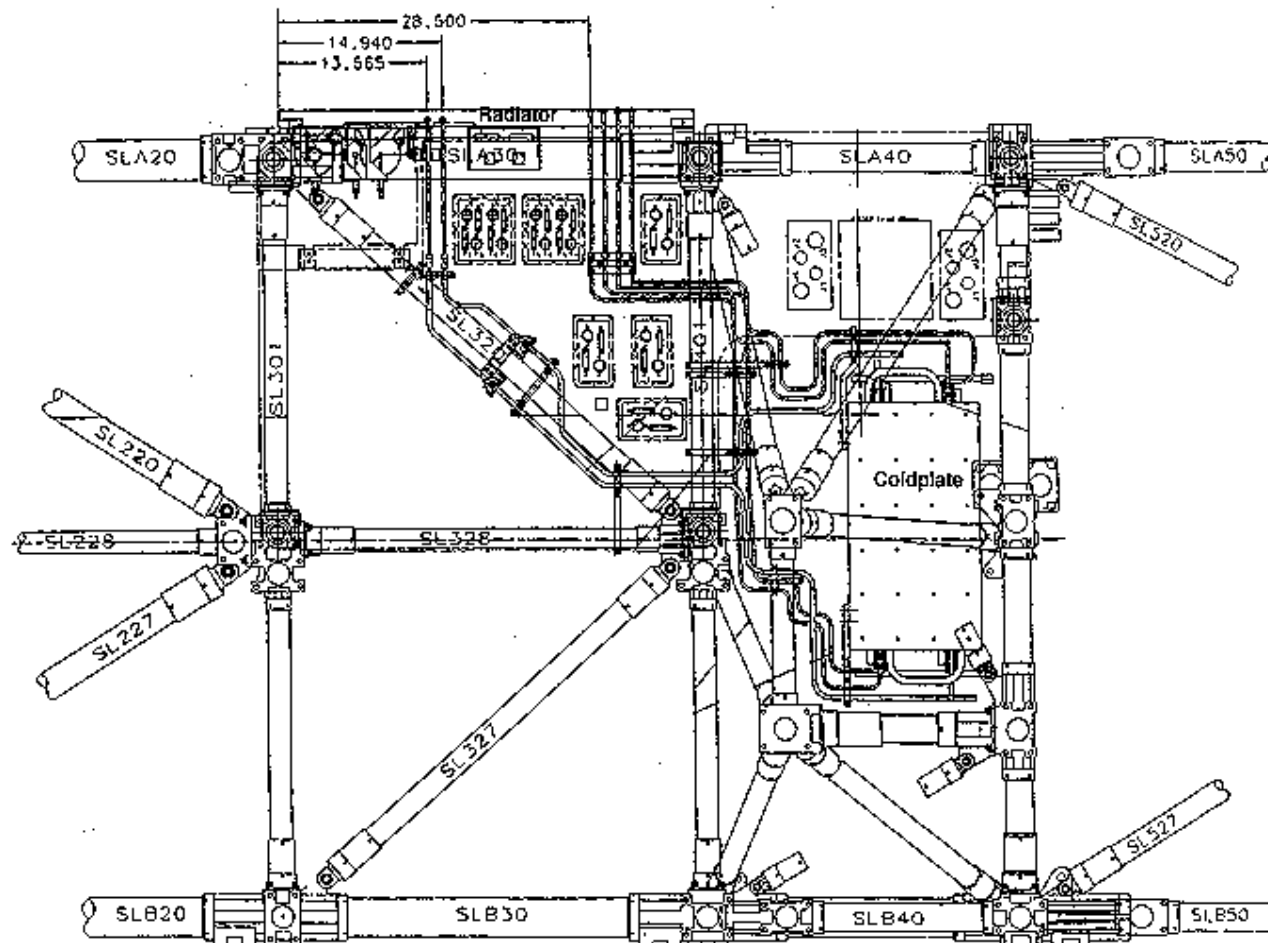
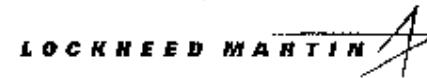


Capillary Pumped Heat Transport System in EOS-TERRA



EOS-TERRA SWIR CPHTS Tubing Layout

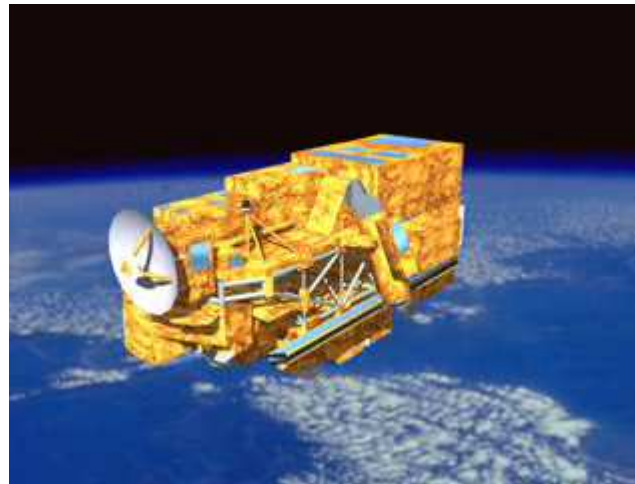
CPHTS – SWIR Tubing Layout



CPLs on TERRA (EOS-AM)

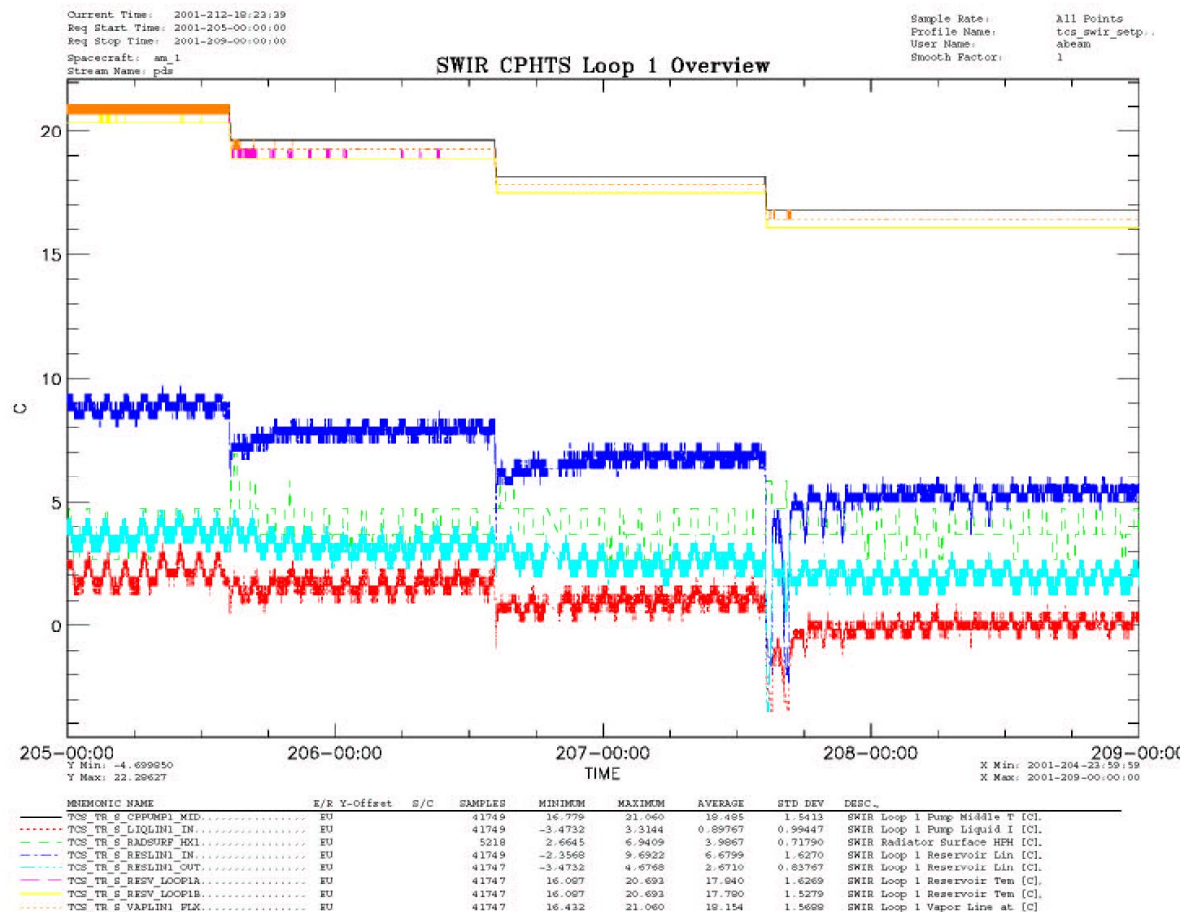


- Two-phase loops (CPLs) are on SWIR, TIR and MOPPIT instruments.
- Terra launched December 18, 1999.
- On the next day, the first CPL system in a flight mission was started successfully.
- All 3 CPLs continue to demonstrate reliable, stable thermal control for their instruments.
- More than 3 years of successful operation



TERRA - Temperature Reset with Stable Control for the ASTER-SWIR Instrument

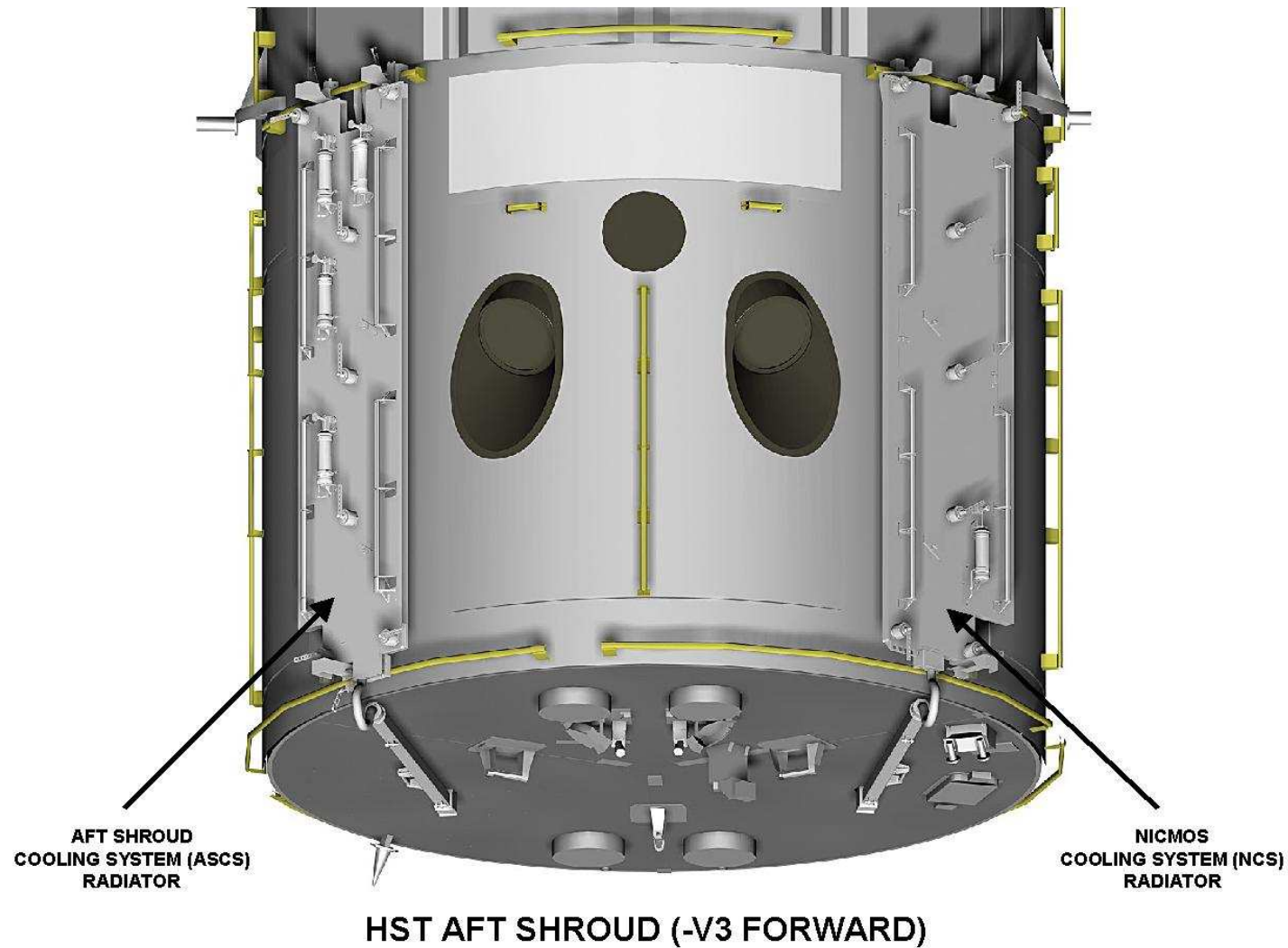
- July of 2001 -ASTER-SWIR cryo-coolers getting too hot.
- CPL loop temperature was reduced by 4.5 °C in 3 steps



Reservoir and Instrument Interface temperatures change as commanded and then remain constant

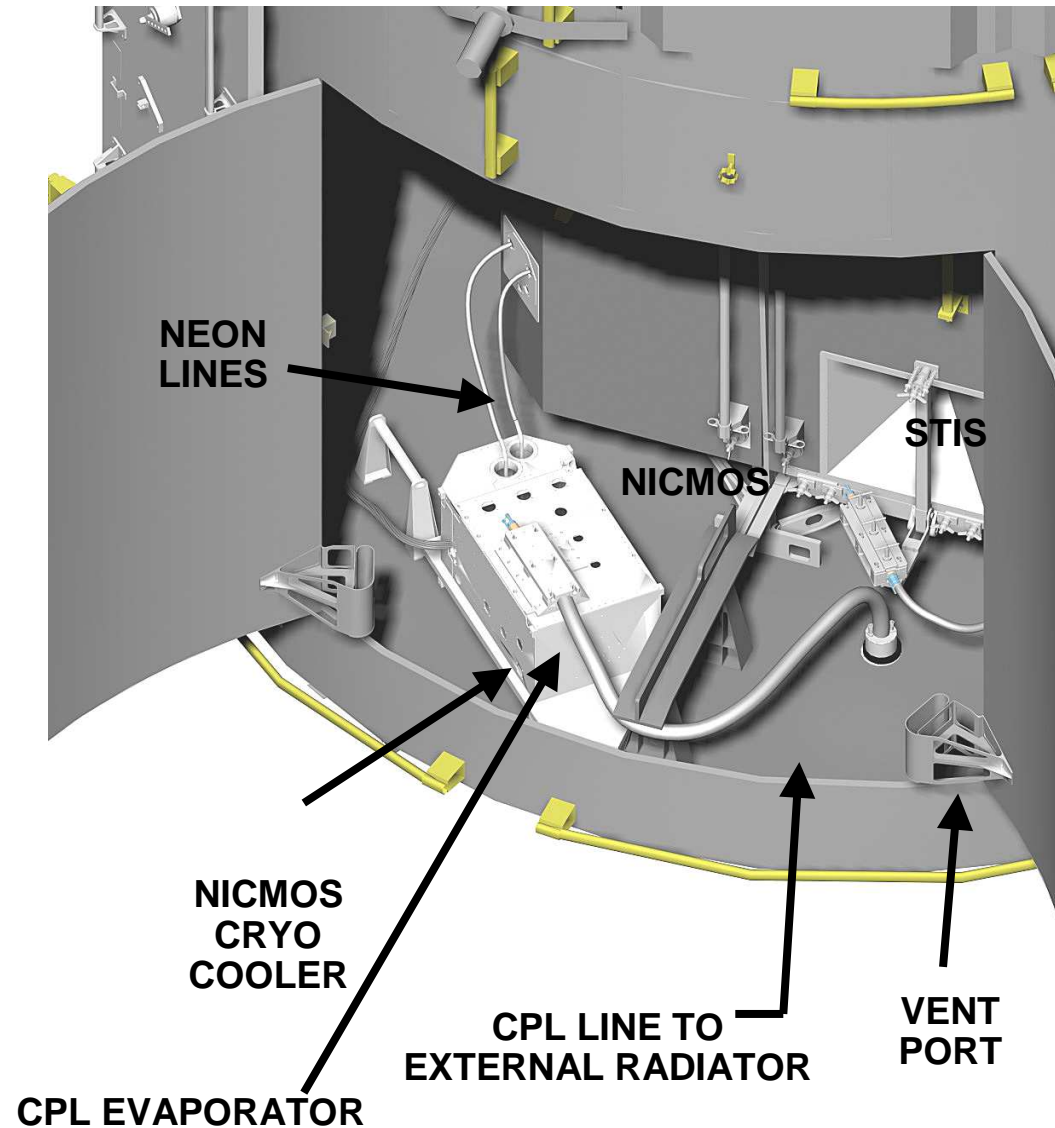
Radiator and various line temperatures adjust according to new set points

External View of NCS and ASCS Systems in HST



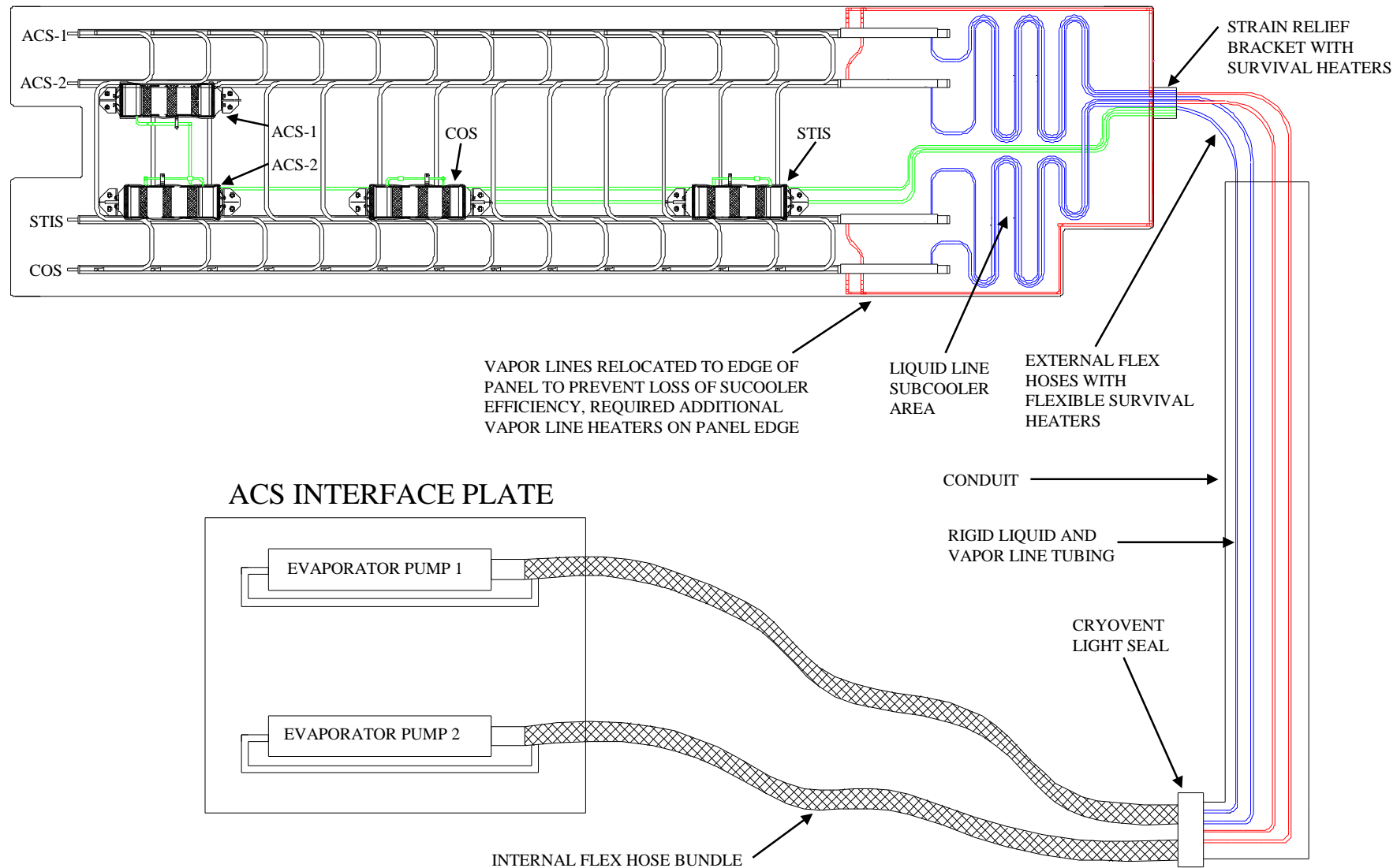
CPL on HST/SM-3B

STS-108, Feb/2002



- **CPL was added to HST Aft Shroud on SM-3B**
- **Astronauts fed CPL evaporator through bottom of shroud, attached it to cryo-cooler, and attached new radiator to handrails.**
- **CPL removes ~ 400 W heat from NICMOS cryocooler which allows the NICMOS sensor to be reactivated.**
- **Tight temperature control**

HST ACS CPLs and ASCS Radiator Design



HST CPL/Radiator Assembly

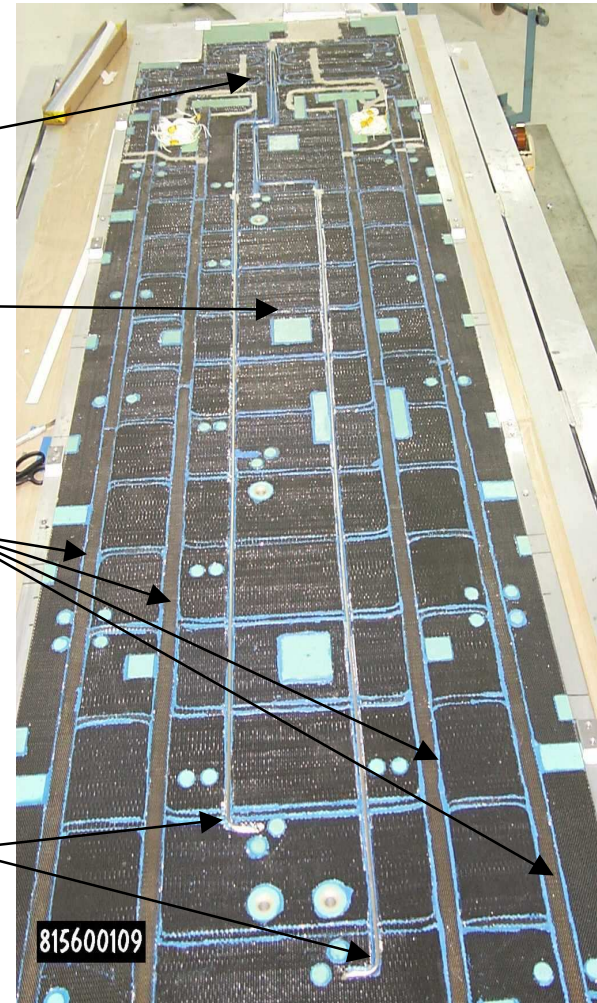


**Subcooler
Section**

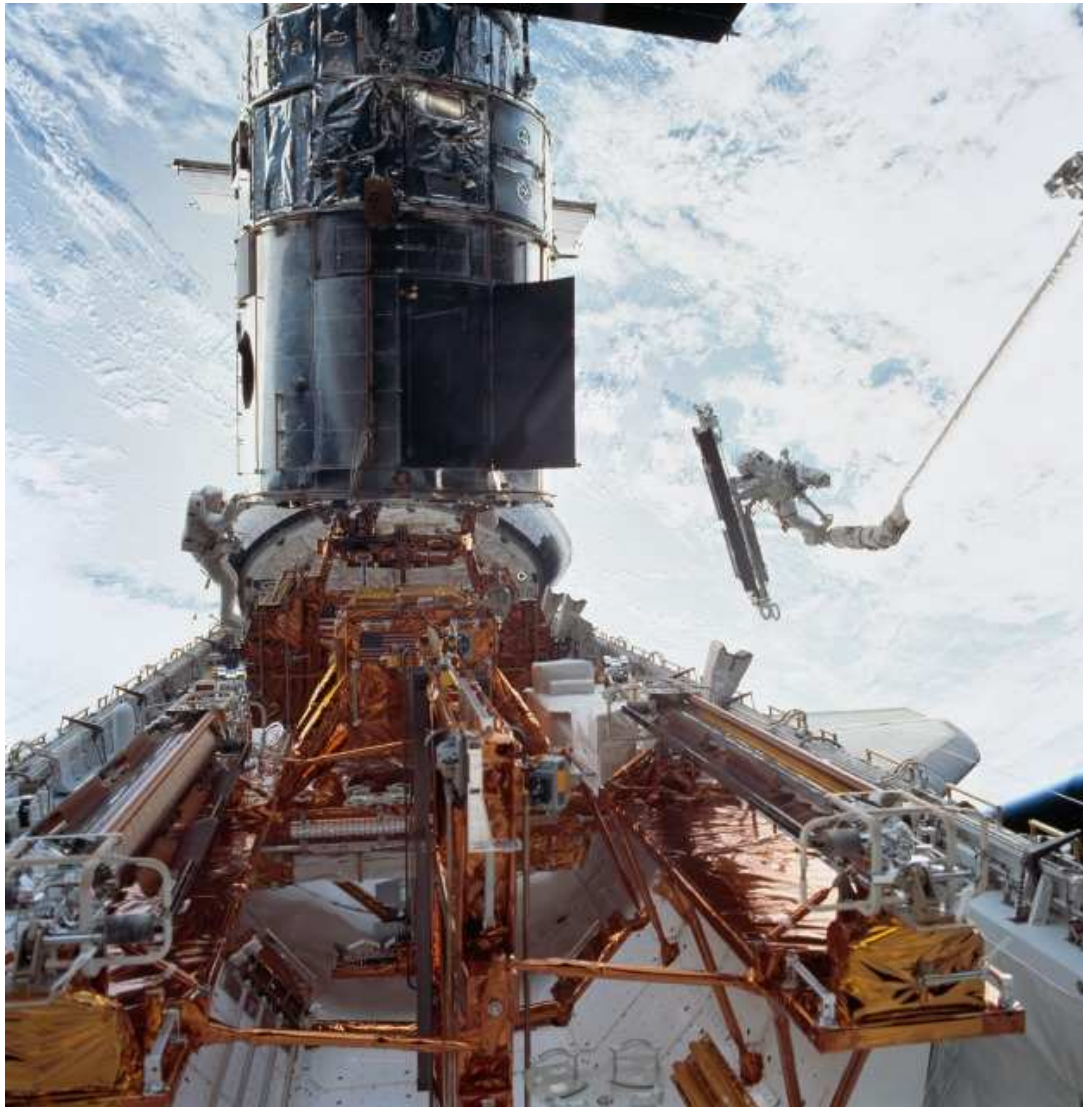
**Isothermalizer
heat pipes**

**Heat Pipe Heat
Exchangers**

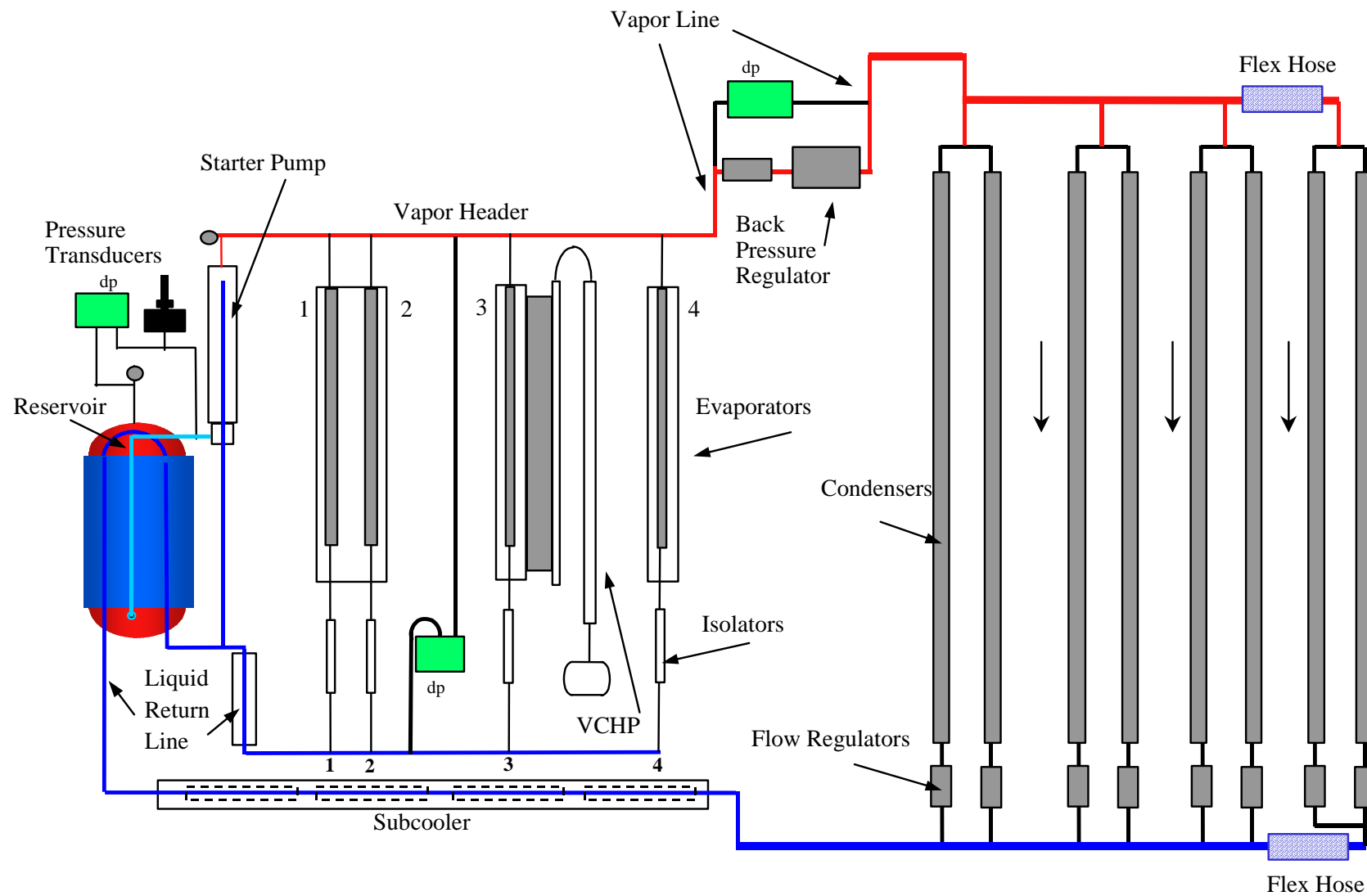
Reservoir Lines



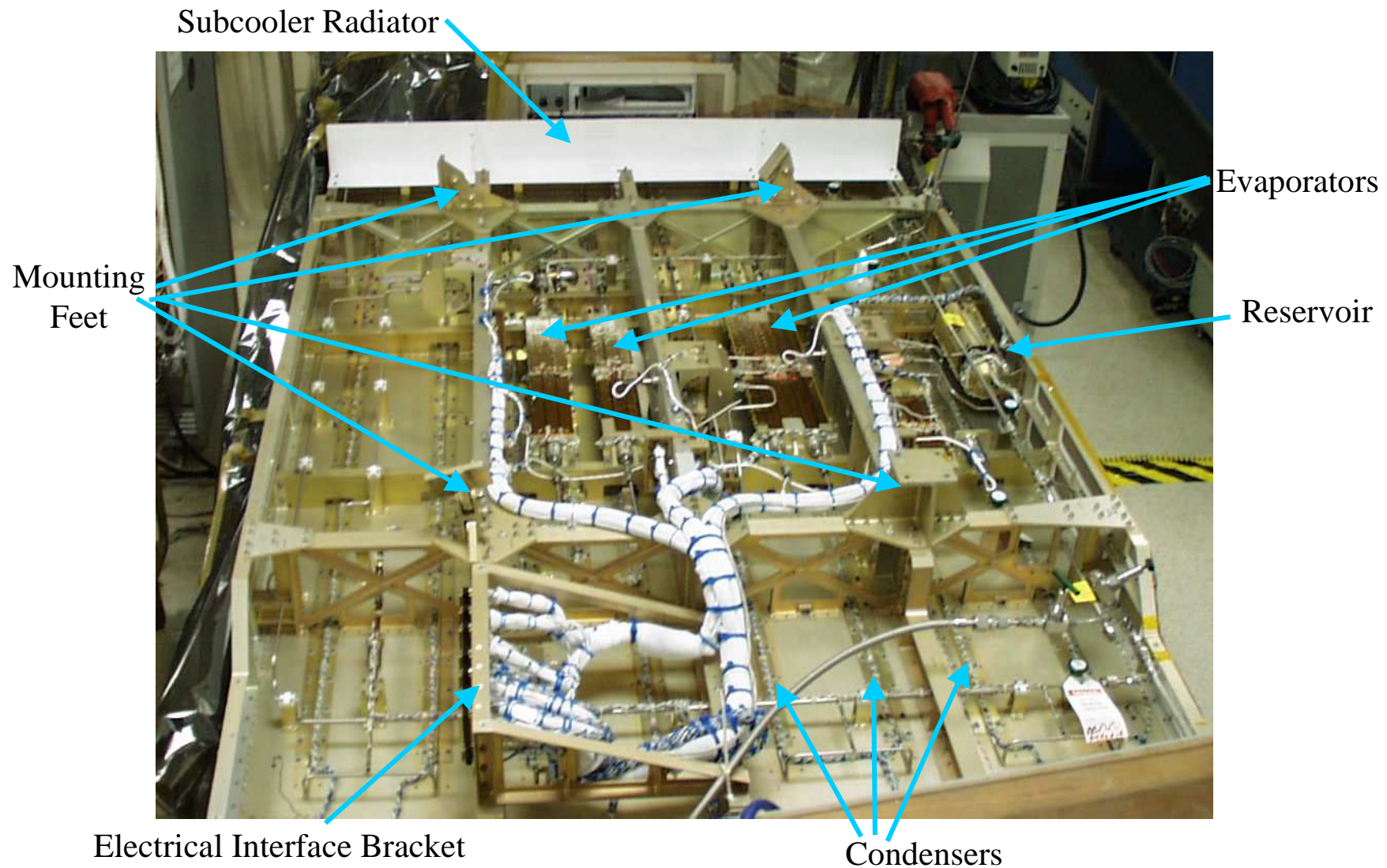
HST Servicing Mission 3B



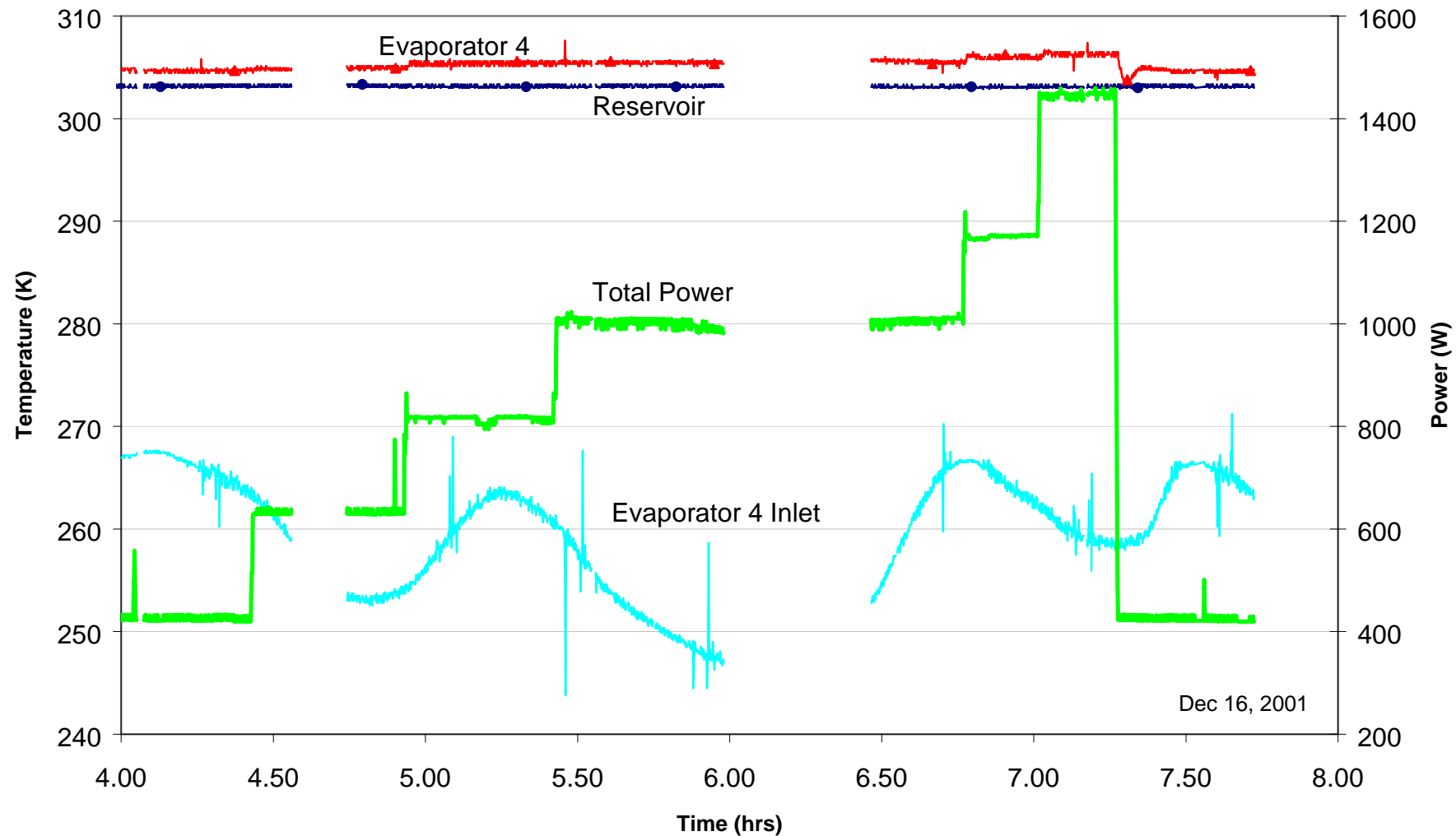
CAPL 3 SCHEMATIC



CAPL3 Radiator Assembly (Upside Down)

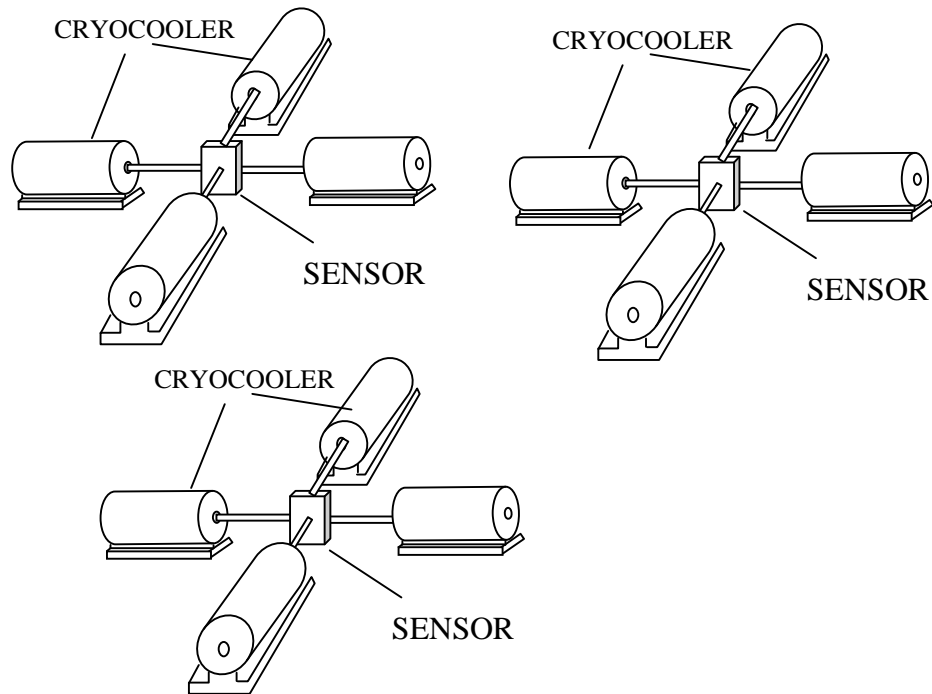


CAPL3 Flight Test Results



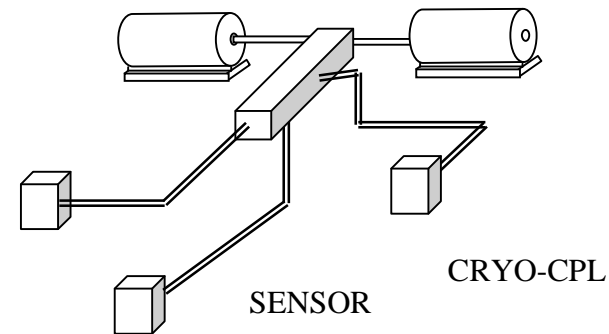
Cryogenic CPL Applications

INDIVIDUALLY COOLED SENSORS



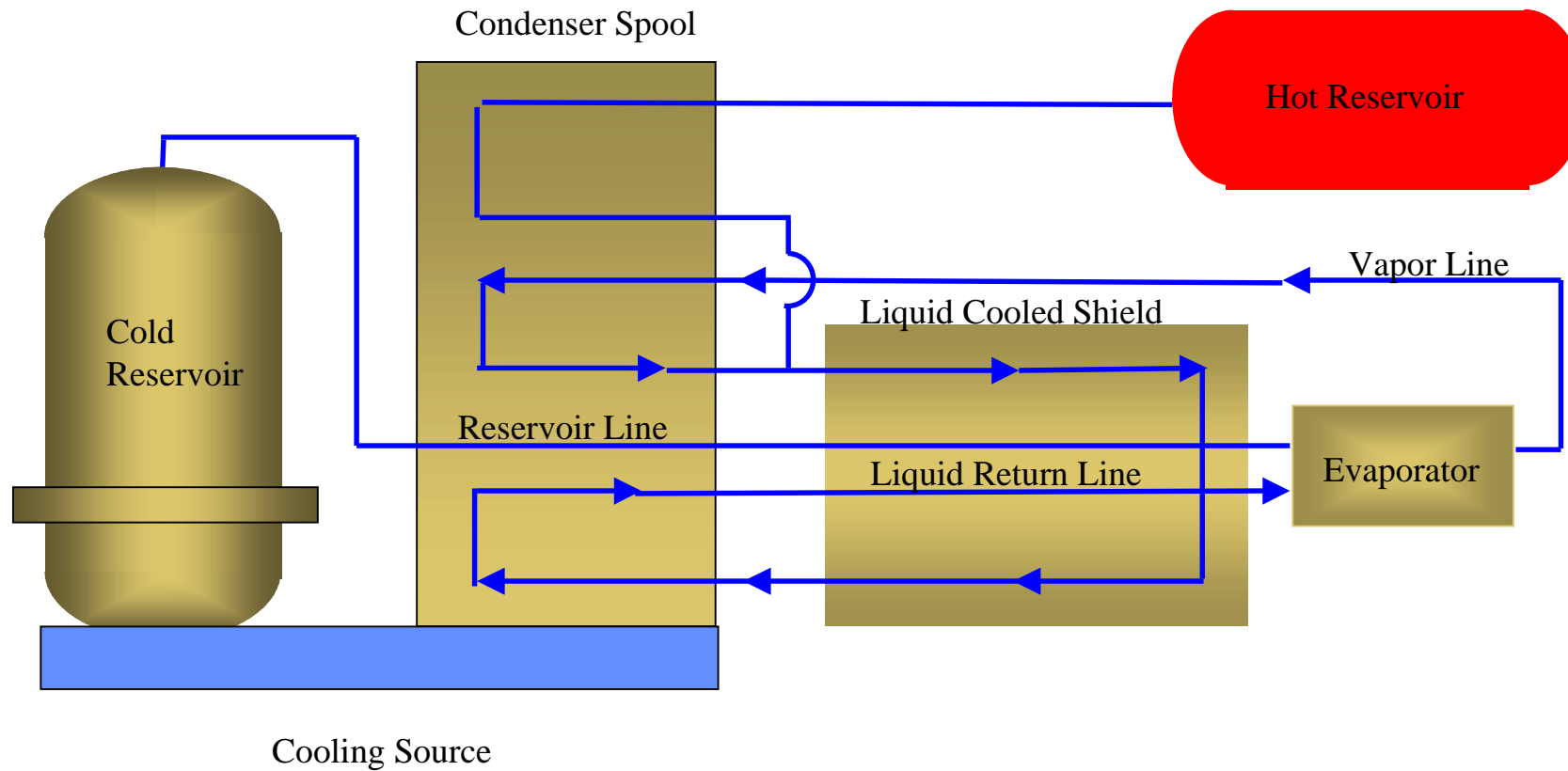
THREE SENSORS,
12 CRYOCOOLERS

CENTRAL BANK OF CRYOCOOLERS

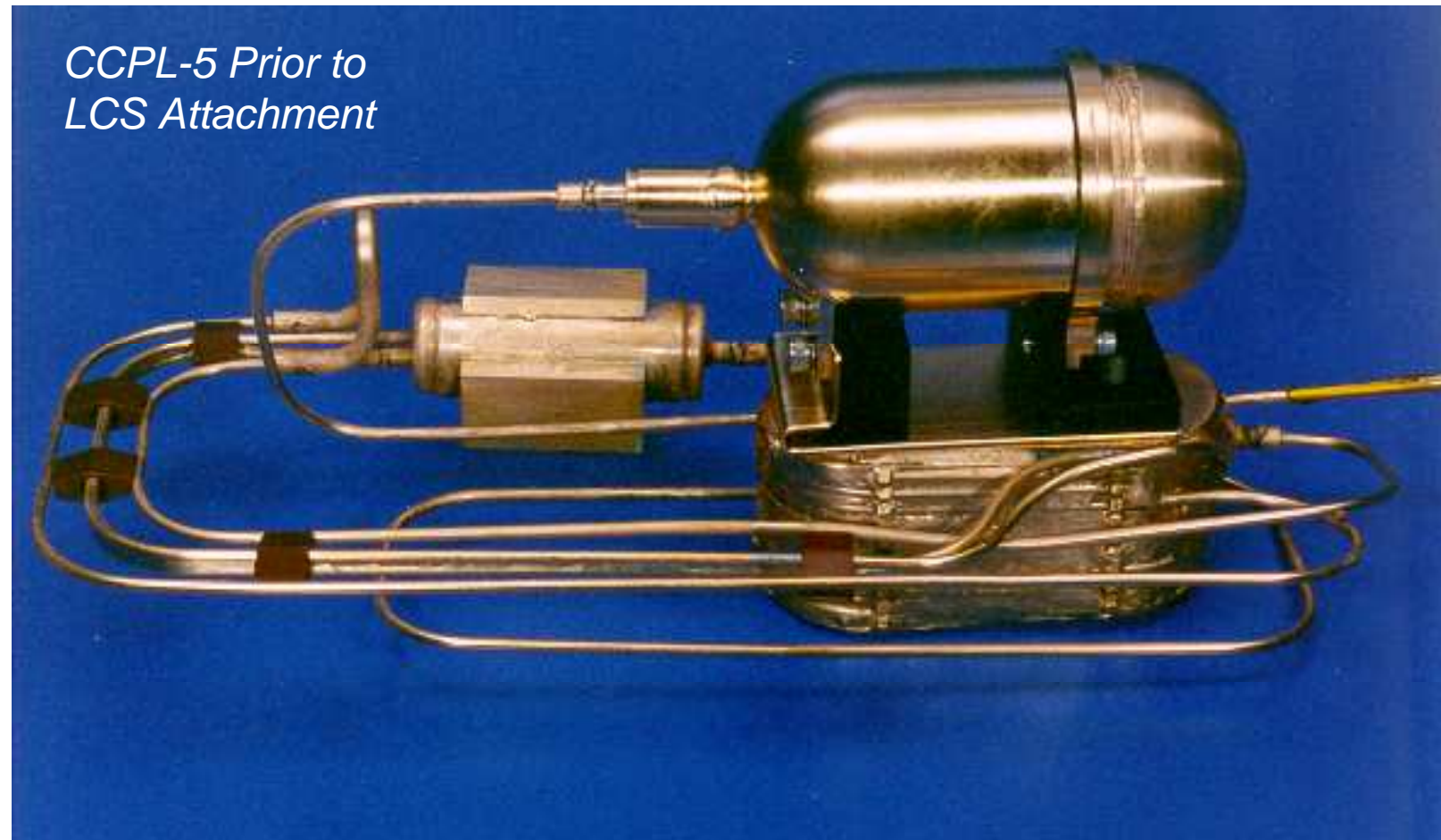


THREE SENSORS
2 TO 6 CRYOCOOLERS

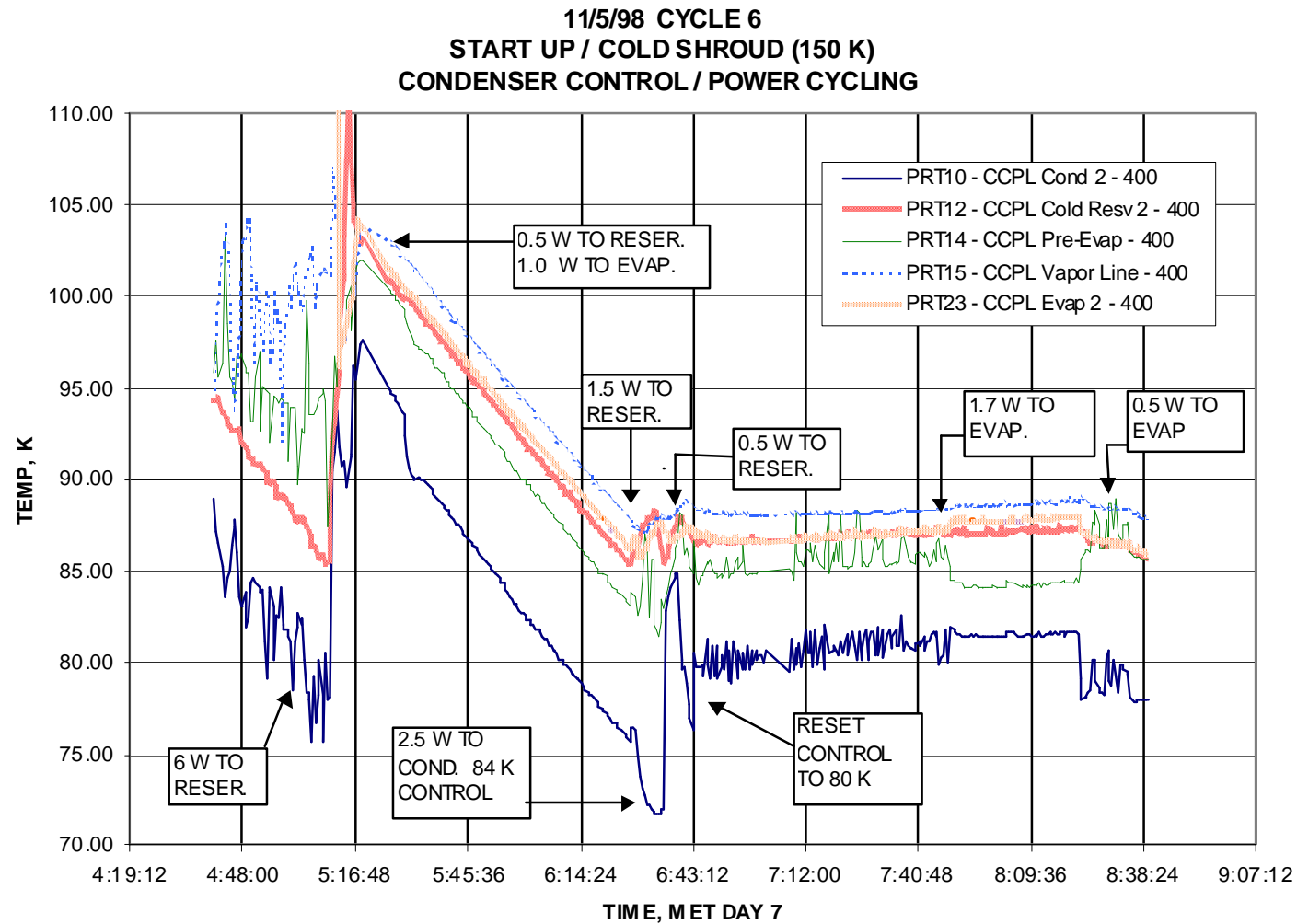
CCPL Flow Diagram



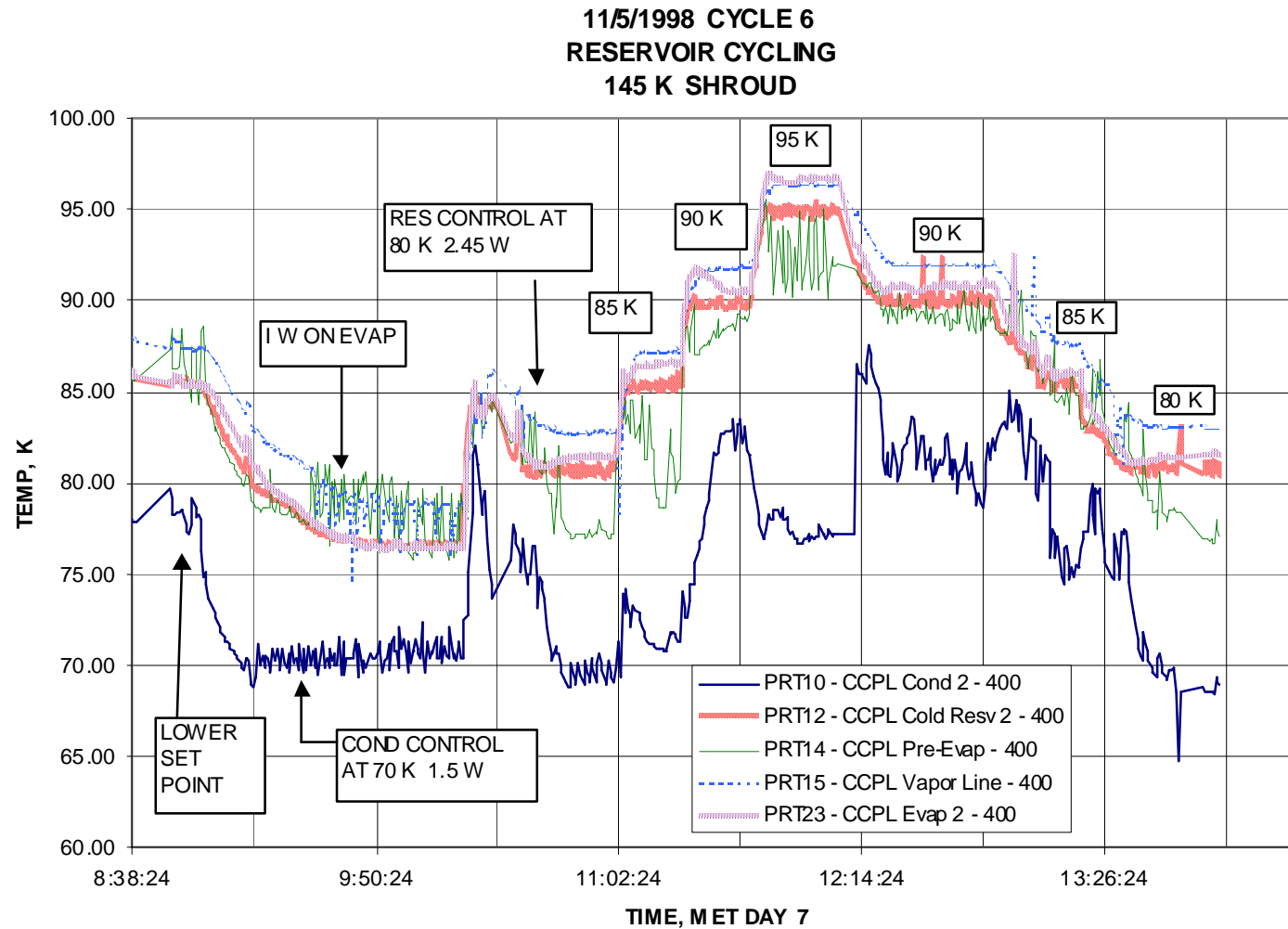
CCPL-5 Flight Unit



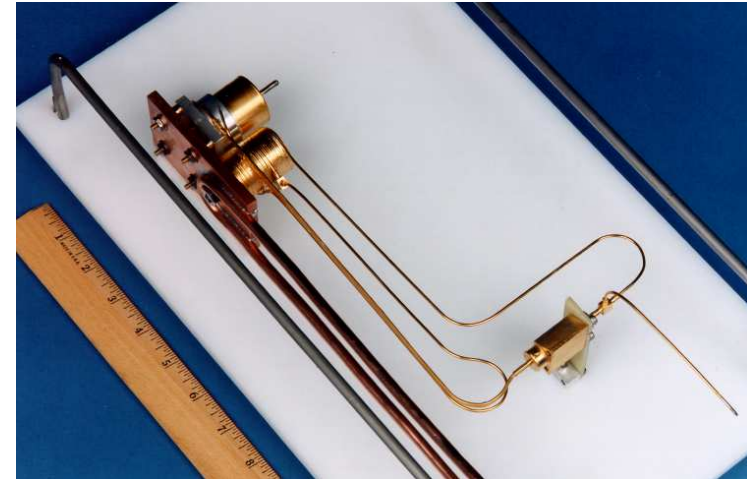
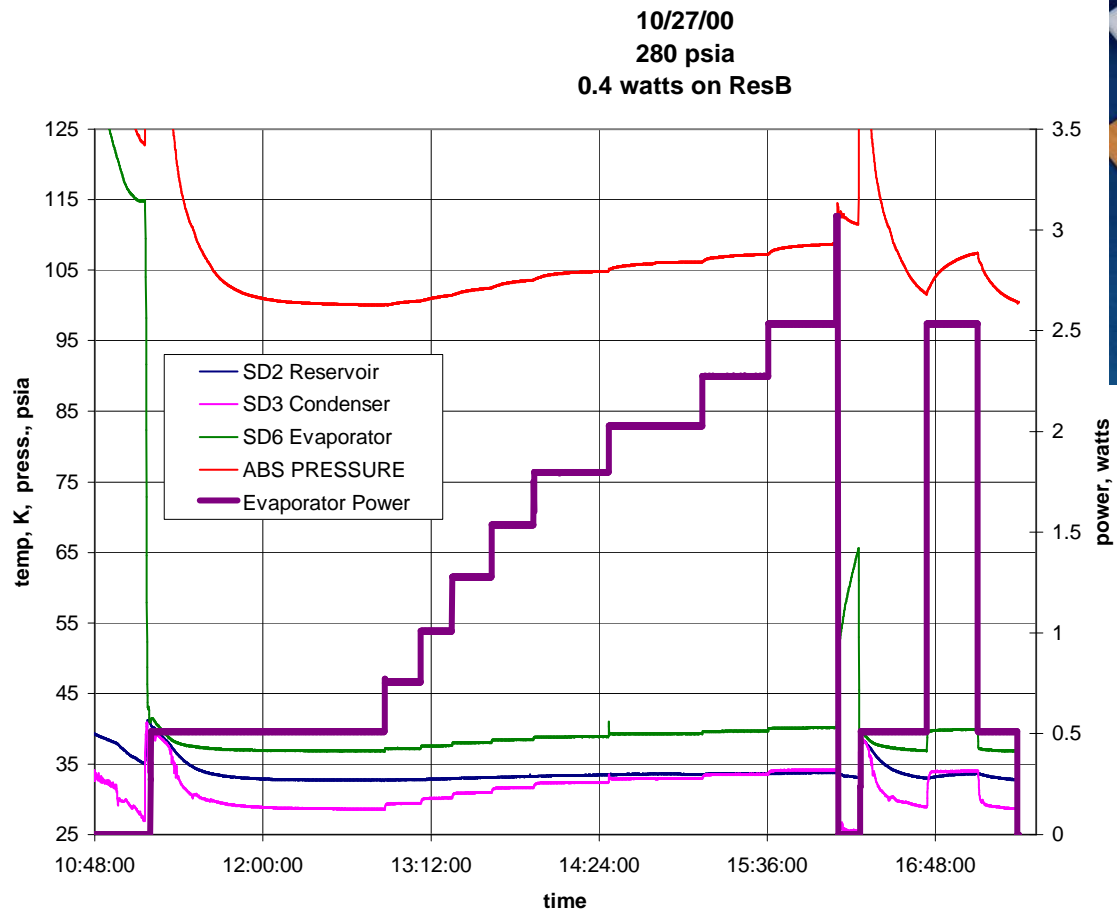
CCPL Flight Test Results



CCPL Flight Test Results

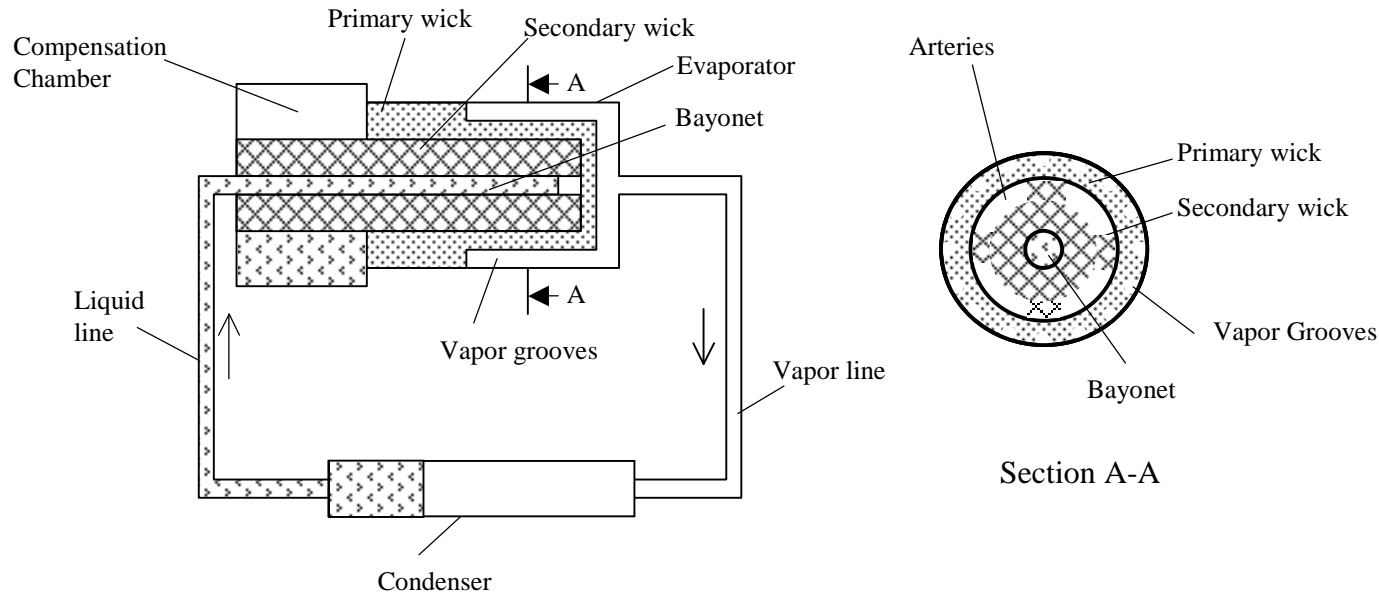


Neon CCPL Ground Test Results



Loop Heat Pipes

Schematic of an LHP



- **Main design features**

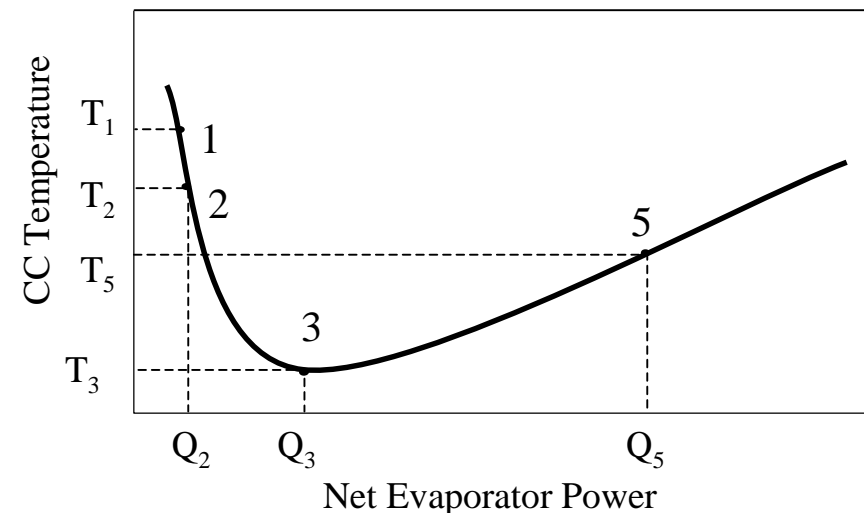
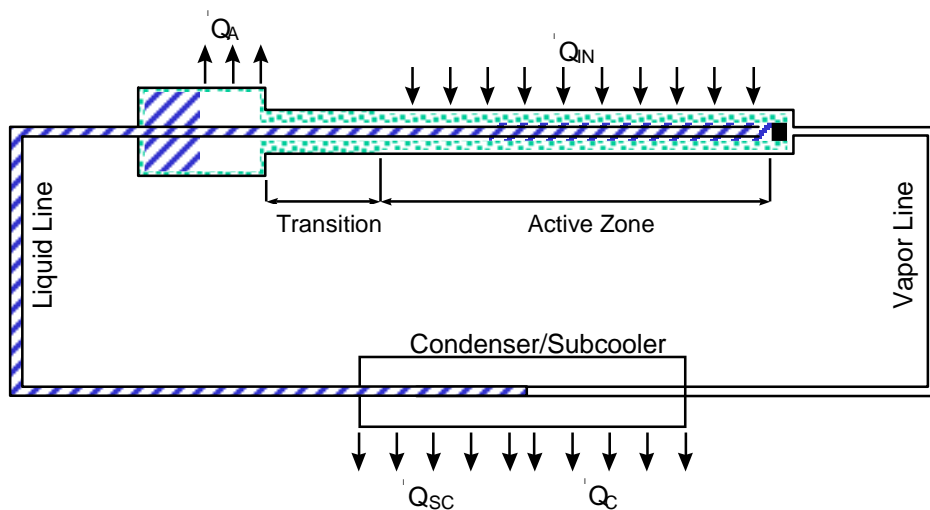
- **The CC forms an integral part of the evaporator.**
- **A primary wick with fine pore sizes provide the pumping force.**
- **A secondary wick connects the CC and evaporator, providing liquid supply.**

Main Characteristics of LHP

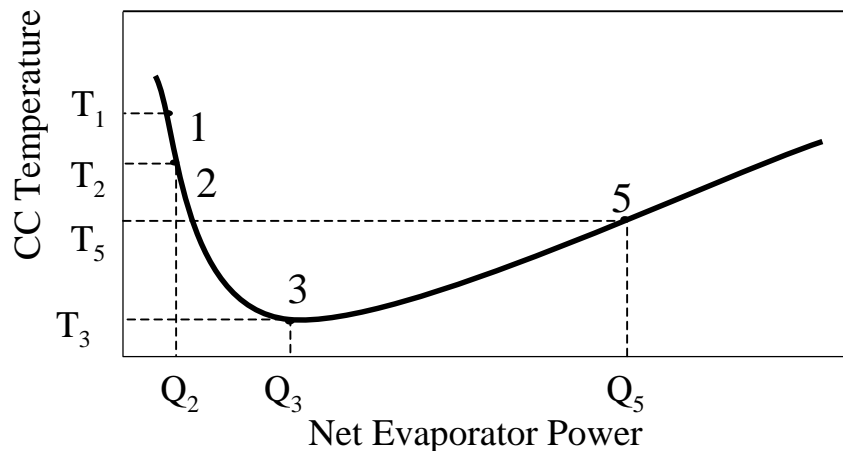
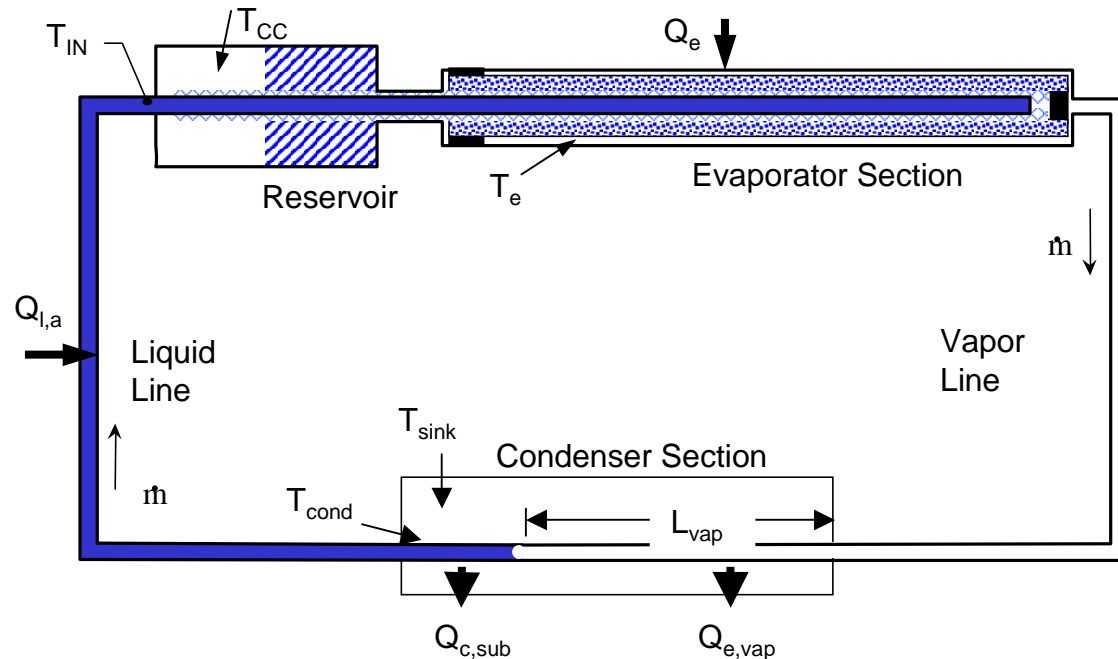
- **High pumping capability**
 - Metal wicks with 1 to 3 micron pores
 - 35 kPa pressure head with ammonia (4 meters in one-G)
- **Robust operation**
 - Secondary wick between CC and evaporator
 - Self start
 - Vapor tolerant
- **CC is plumbed in line with flow circulation**
 - Operating temperature depends on operating conditions.
 - Thermodynamic constraints exist.
 - Large external power may be required for temperature control.
 - Loop shutdown
 - Limited growth potential
 - » Single evaporator most common

LHP Operating Temperature

- The LHP operating temperature is governed by the CC temperature.
- The CC temperature is a function of
 - Evaporator power
 - Condenser sink temperature
 - Ambient temperature
 - Evaporator/CC design
- As the operating condition changes, the CC temperature will change during the transient, but eventually reaches a new steady temperature.
- The loop operating temperature can be controlled at a desired set point.



Energy Balance in LHP Operation



$$Q_e = Q_{e,cc} + Q_{e,vap}$$

$$Q_{e,cc} = G (T_e - T_{cc})$$

$$Q_{e,vap} = \dot{m} \lambda$$

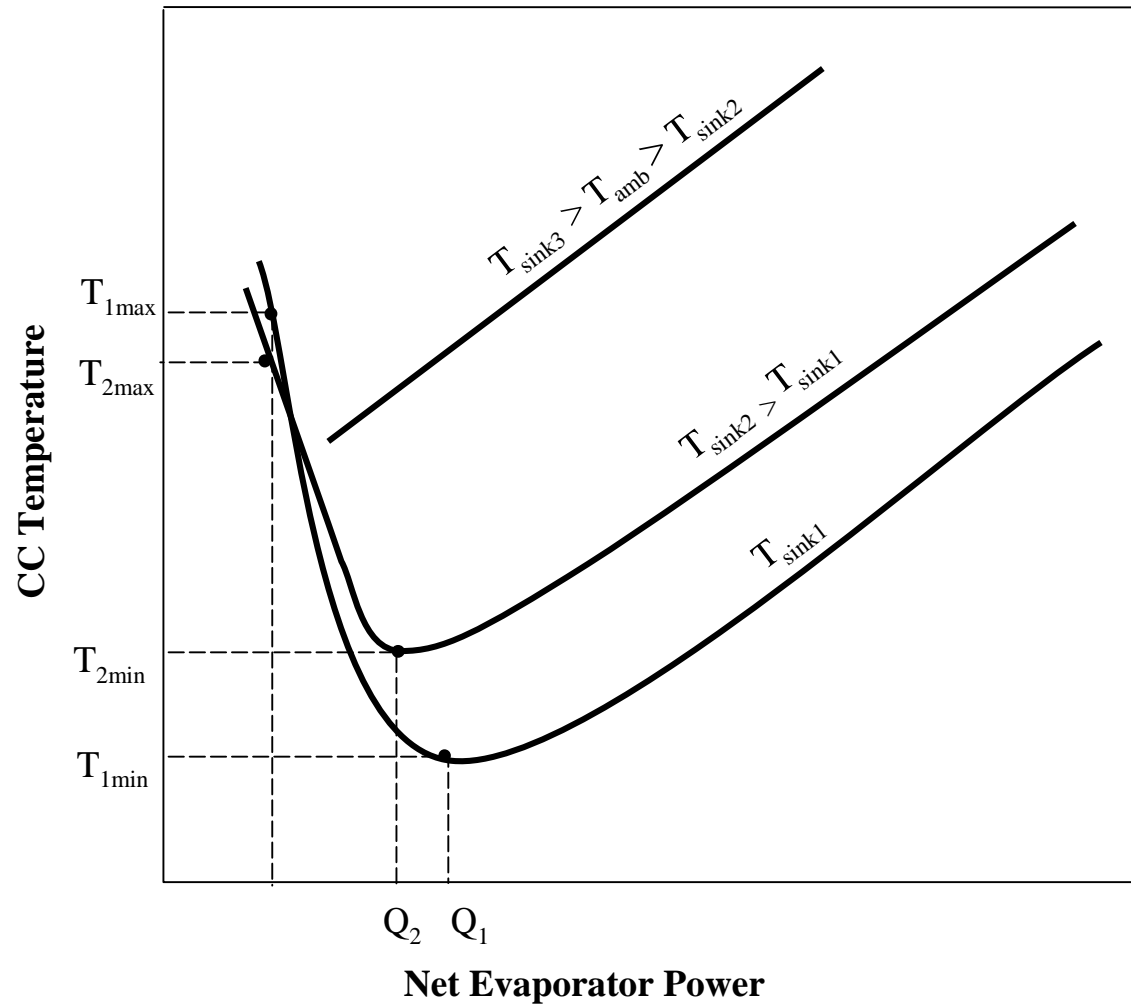
$$L_{vap} = Q_{e,vap} / [h \pi D (T_{cc} - T_{sink})]$$

$$T_{in} - T_{cond} = Q_{l,a} / (\dot{m} C_p)$$

$$Q_{e,cc} = \dot{m} C_p (T_{cc} - T_{in})$$

$$\Delta P = \lambda (T_e - T_{cc}) / (T_{cc} \Delta v)$$

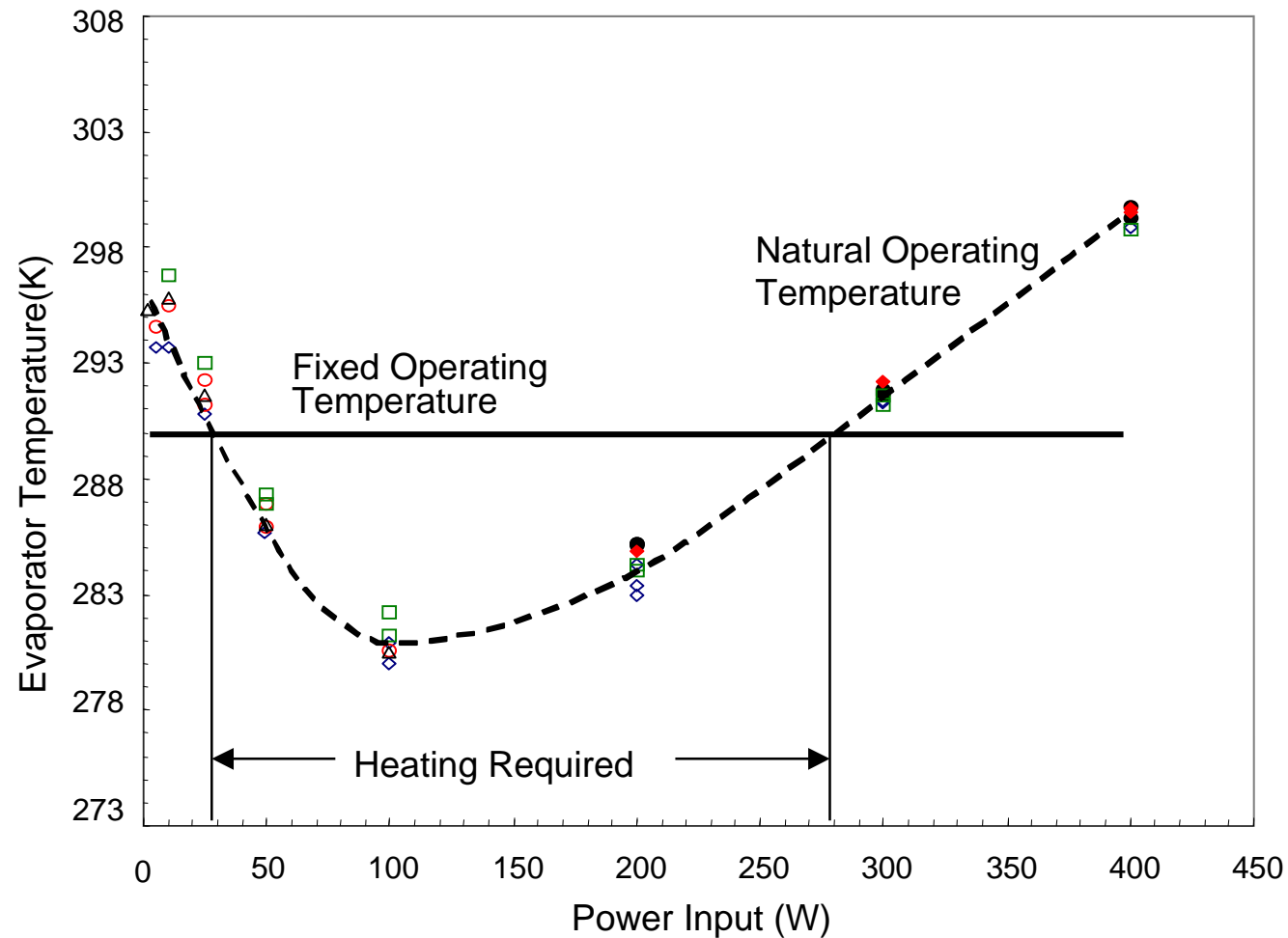
Effect of Sink Temperature on CC Temperature



LHP Operating Temperature Control

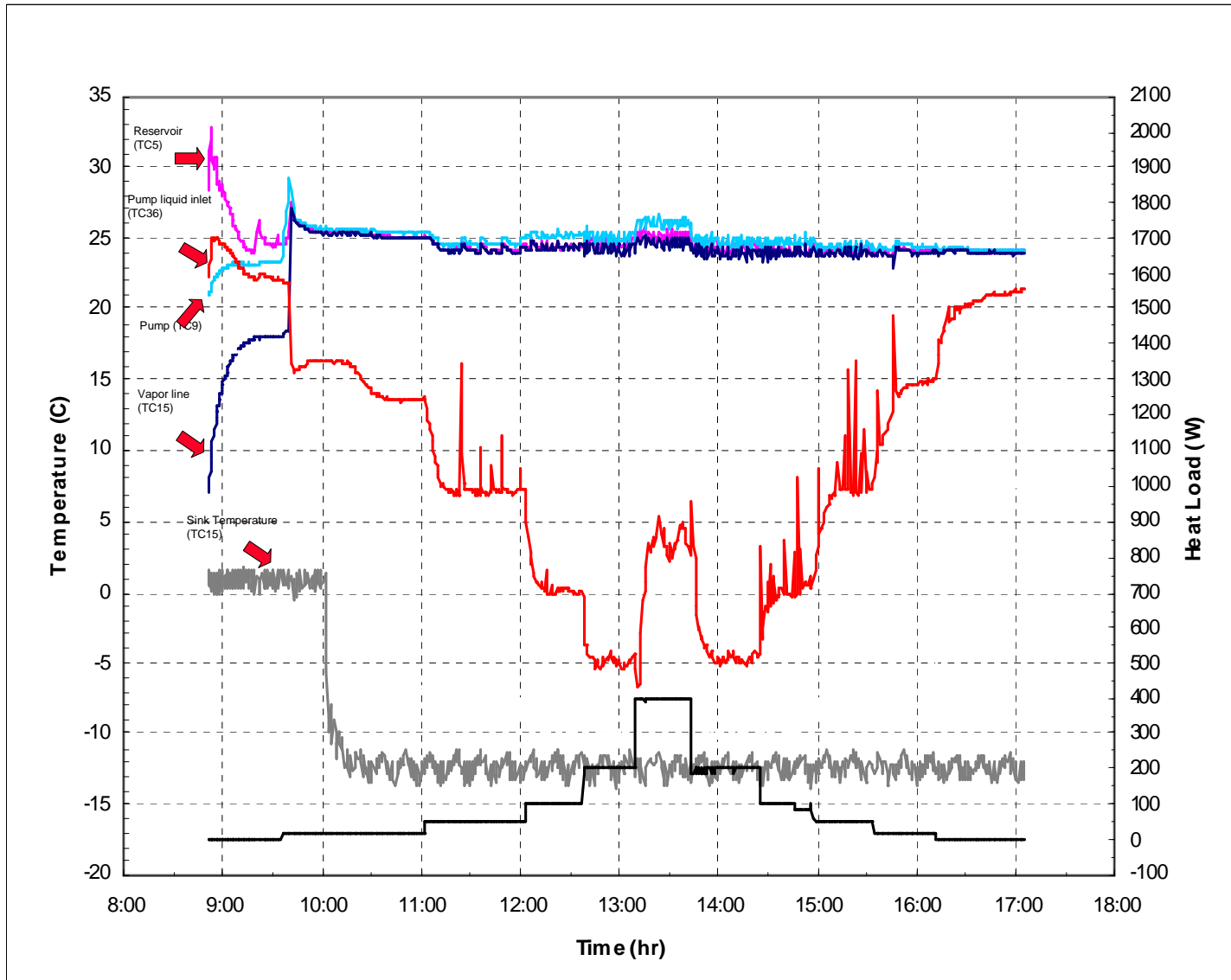
- **Control LHP operating temperature by controlling the CC at a desired set point temperature.**
- **Heat the CC above its natural equilibrium temperature.**
 - **Control is lost once condenser heat dissipating capability is exceeded.**
 - **Control may be lost at low heat loads.**
 - **Overall conductance decreases.**
 - **Power requirement depends on heat load and sink temperature.**
 - **Alternate methods exist by heating the liquid line.**
 - » **Cross strap the vapor and liquid line**
 - » **VCHP**
- **Cool the CC below its natural equilibrium temperature**
 - **Practical only at low heat loads**
 - **Use TEC or secondary evaporator.**

LHP Operating Temperature Control



LHP Operating Temperature Control

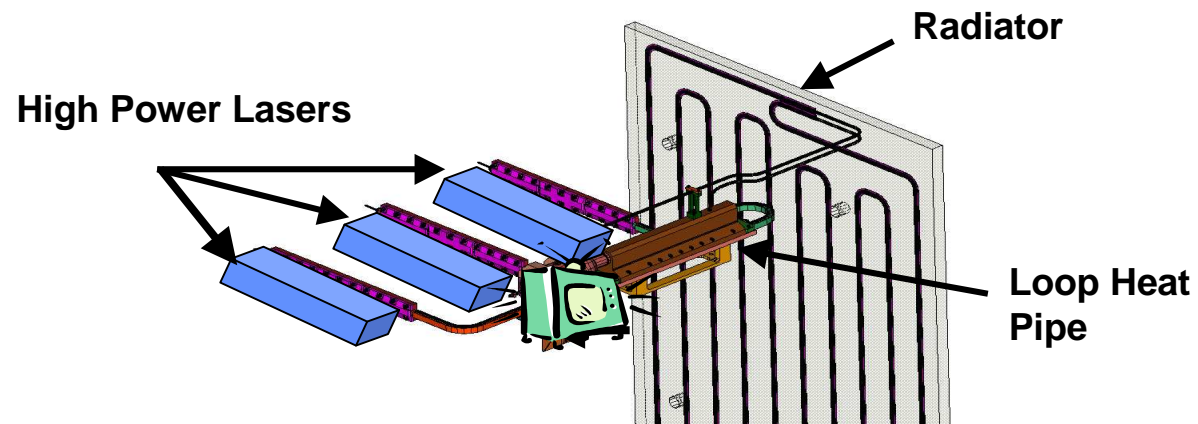
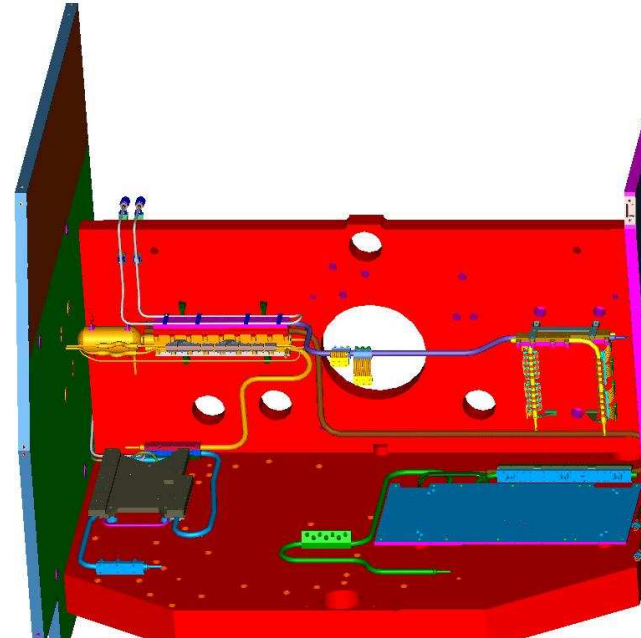
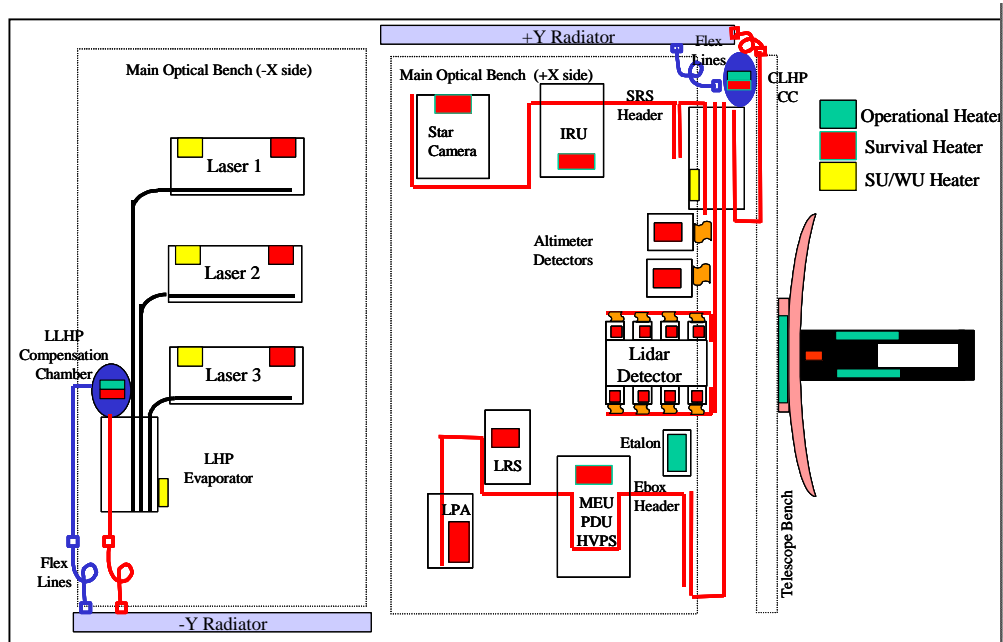
NRL LHP



LHP Development History

- **1985** U.S. Patent granted to Maidanik, et al.
 - **1989** LHP flight experiment on GRANAT (Russia)
 - **1993** Multiple evaporator LHP
 - **1997** American LHP flight experiment (NASA)
 - **1997** Russian LHP flight experiment (NASA/DOD)
 - **1999** LHPs on commercial satellites (Boeing)
 - **2002** Cryogenic LHPs - nitrogen, hydrogen, neon (NASA/DOD)
 - **2003** LHPs on ICESAT - GLAS (NASA)
 - **2003** LHPs on COM2PLEX flight experiment (ESA)
 - **2004 (planned)** LHPs on on EOS - AURA (NASA)
 - **2004 (planned)** LHPs on GOES (NASA)
 - **2004 (planned)** LHPs on SWIFT - BAT (NASA)
 - **2004 (planned)** LHPs on AMS (NASA/ESA)
 - **2004 (?)** LHPs ground applications (US company)
-

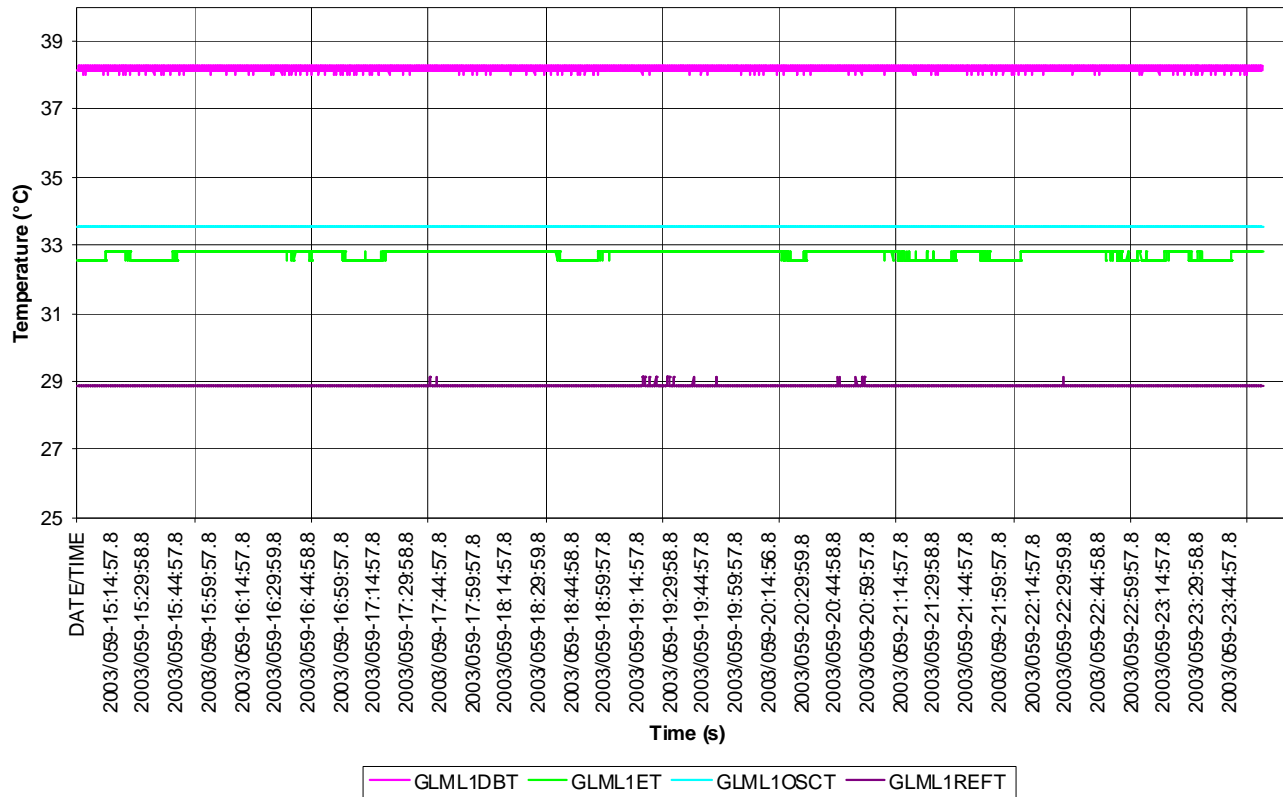
GLAS Laser and Component LHPs



GLAS Laser Temperatures

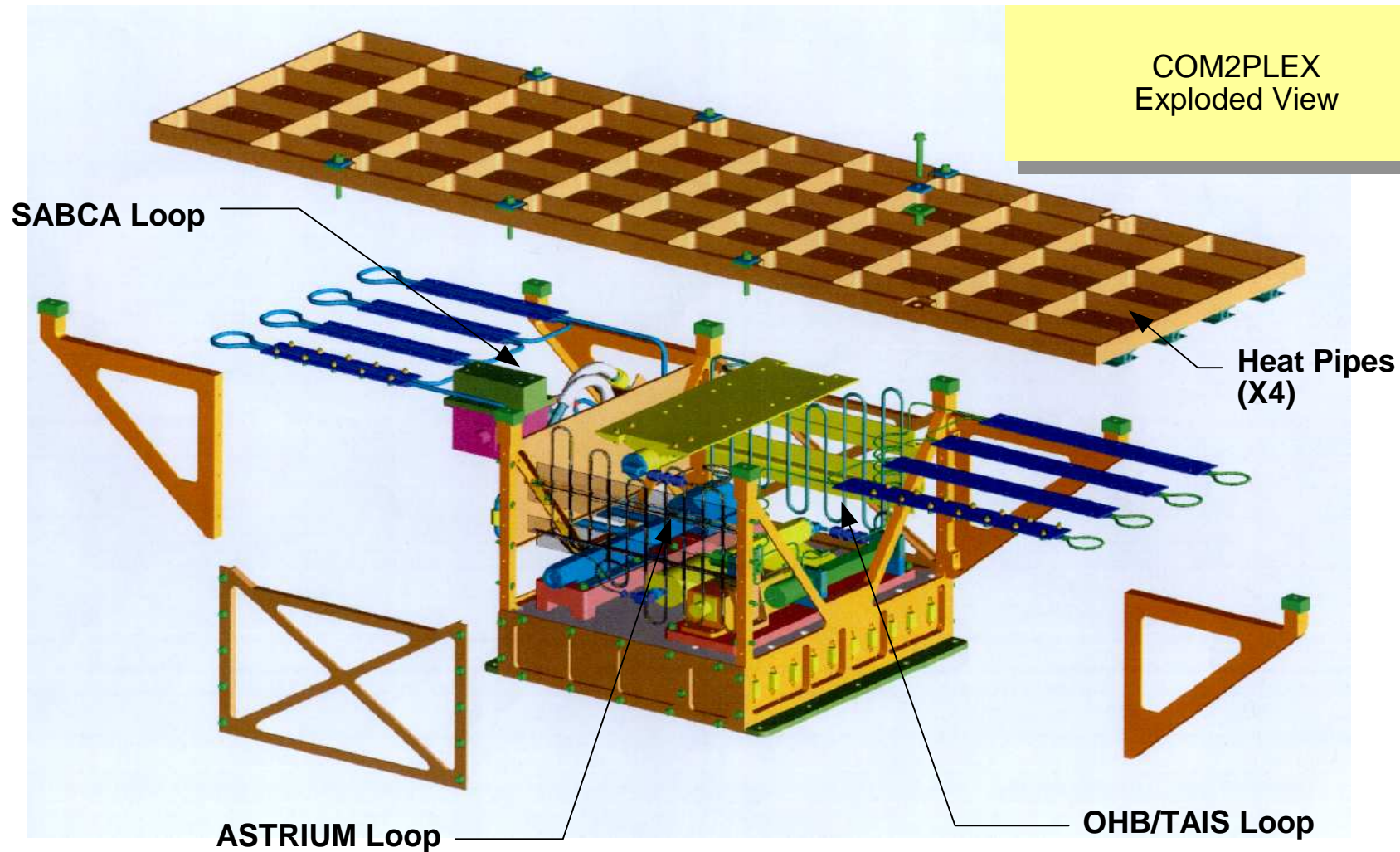
- LLHP Active Control is finer than can be measured in the laser telemetry when the LHP is at full 110 W of power

GLAS Laser Transient Data 02/28/03 (Instrument fully powered)

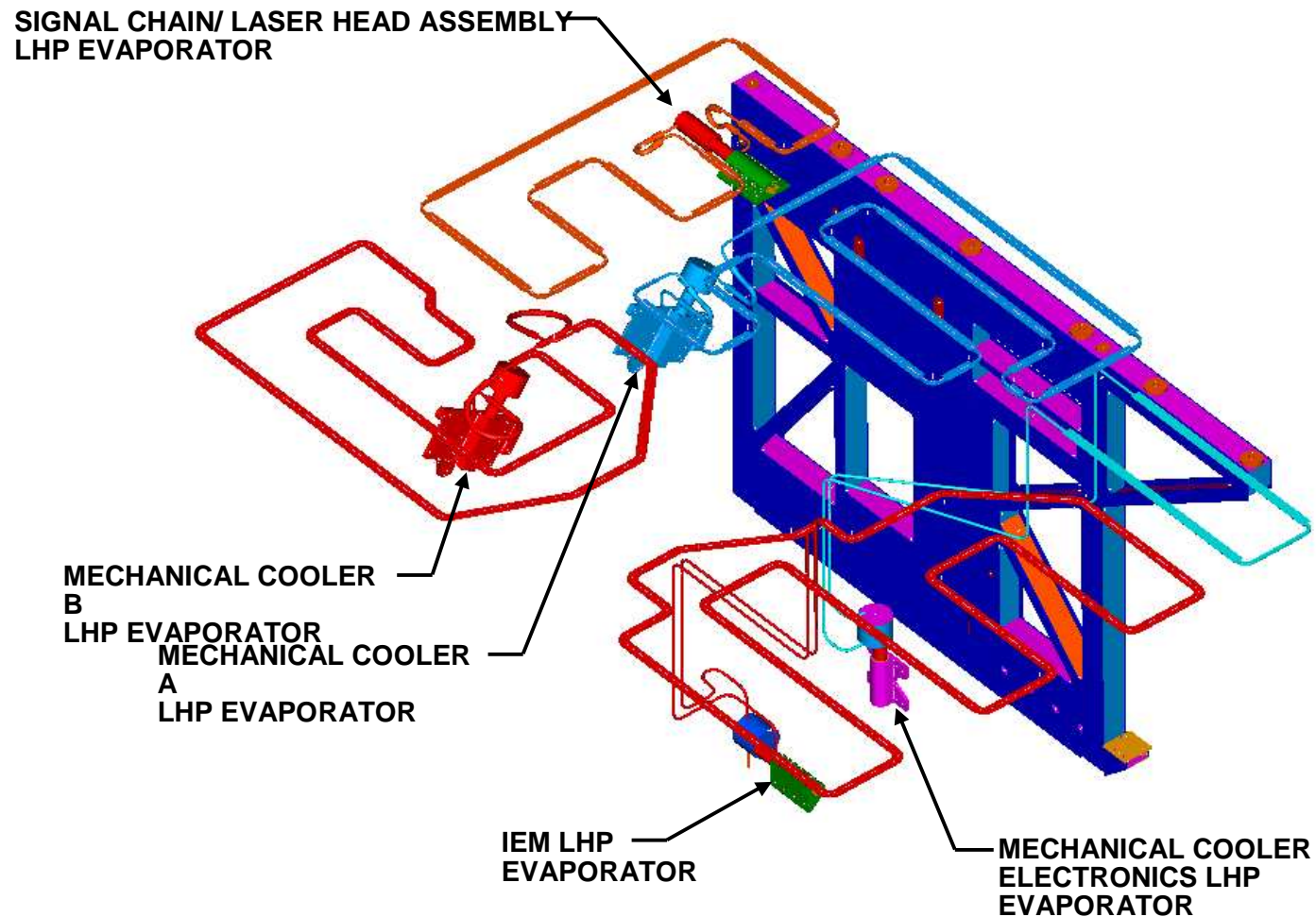


COM2PLEX Experiment Systems (ESA)

Onboard Space Shuttle Columbia 2/2003



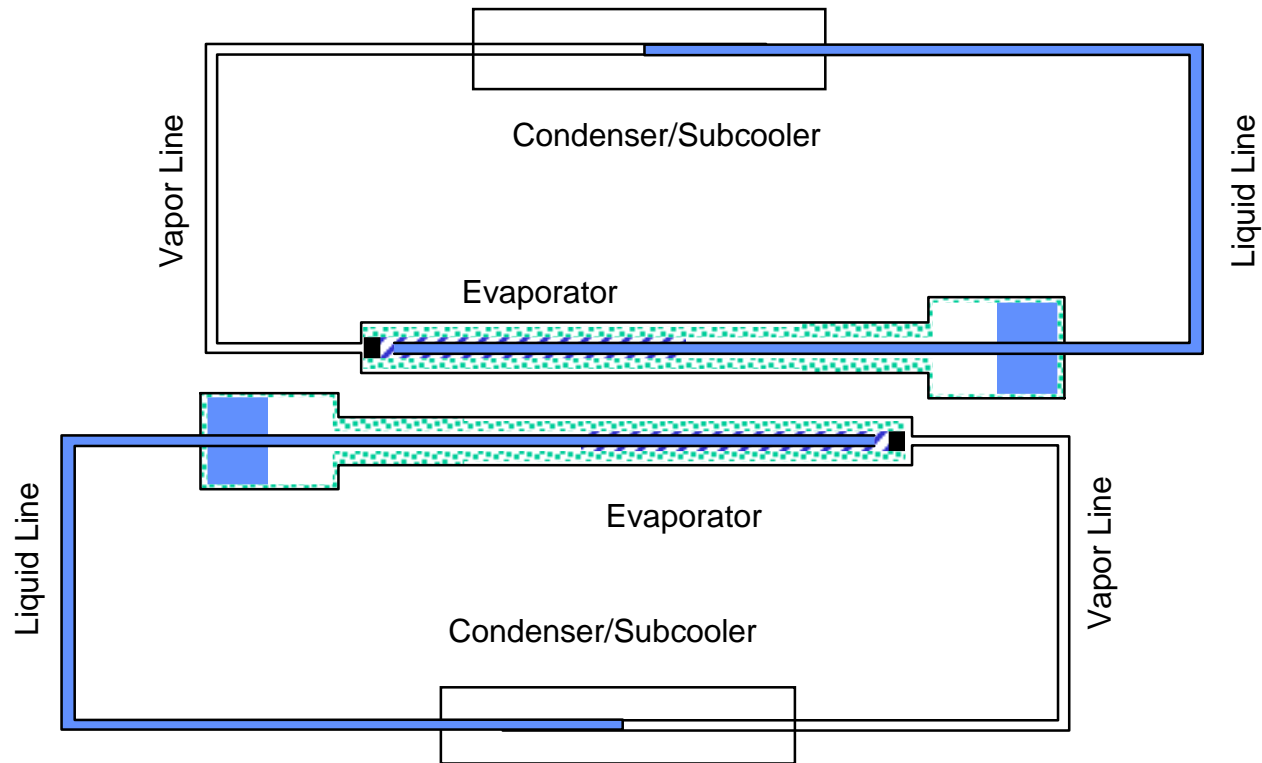
EOS-Aura TES Instrument Loop Heat Pipe Layout



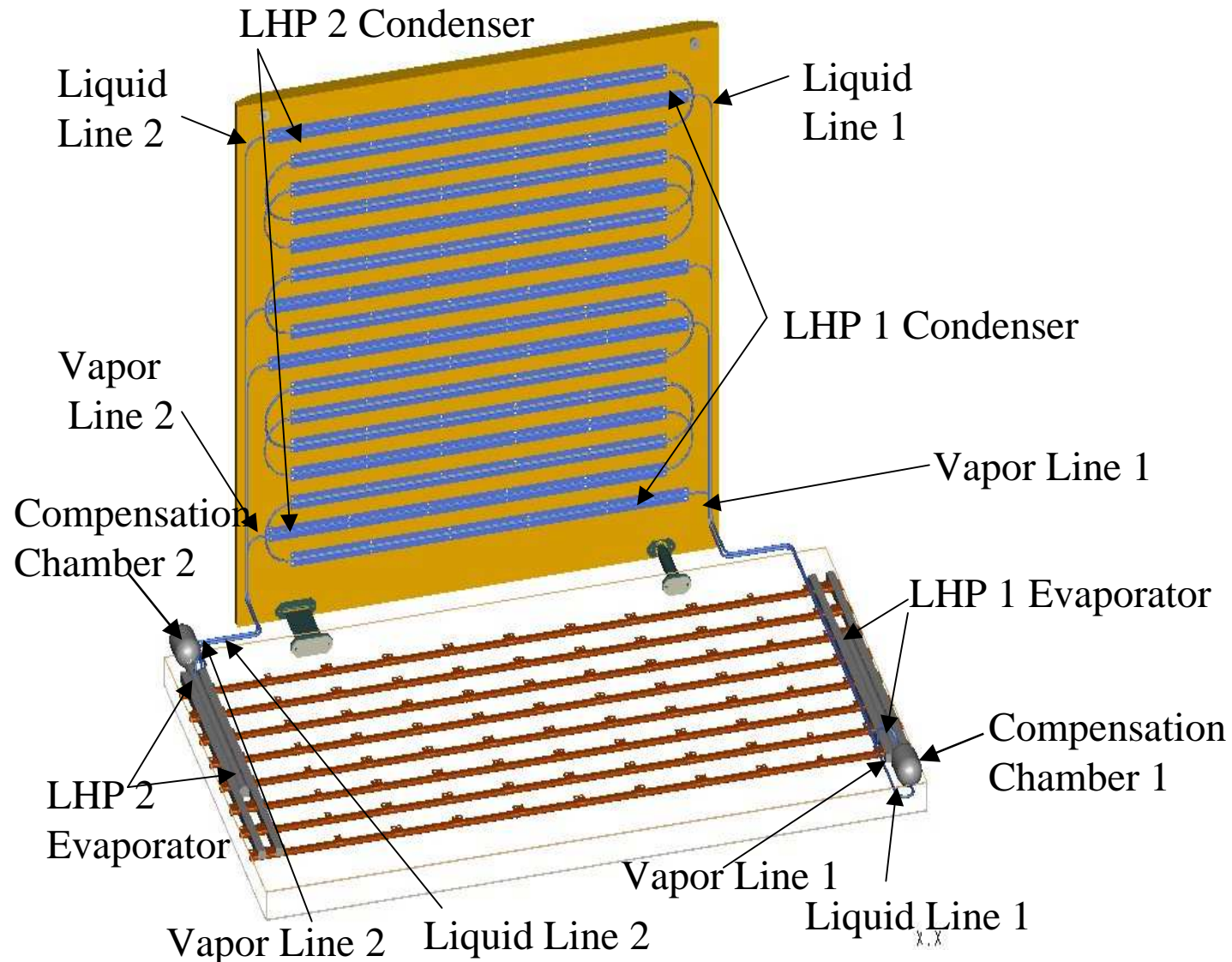
Multiple Single-Evaporator LHPs

- **Reasons to use multiple LHPs for the same heat source**
 - Increase the overall heat transport capability
 - Increase system reliability with redundant loops
 - Reduce temperature gradients of heat source
 - Alternative to an LHP with multiple evaporators
- **Issues of multiple LHPs**
 - Some LHPs may not start and hence remain inactive over a range of heat load.
 - LHPs may operate at different temperatures.
 - Each LHP may carry a different heat load.
 - Heat source temperature will vary with heat load distribution.
 - Temperature gradient on heat source may be higher than expected.
- **Design implications**
 - Enough margin for heat transport
 - Enough margin for temperature gradients
 - Each LHP needs a temperature controller in order for them to operate at the desired temperature.

Schematic of Multiple LHPs



SWIFT BAT LHPs



LHP Start-up

- LHP start-up is a complex phenomenon.
- LHP can self start by directly applying power to the evaporator without pre-conditioning.
- Self-start does not always imply instant or quick start.
- Start-up depends on initial conditions inside evaporator.
 - Evaporator vapor grooves
 - » Liquid filled: superheat required for nucleate boiling
 - » Vapor presence: instant evaporation
 - Evaporator liquid core
 - » Liquid filled: low heat leak, small temperature overshoot
 - » Vapor presence: high heat leak, large temperature overshoot
- A minimum power is required for start-up under certain conditions.
- Current practice is to use a starter heater to enhance start-up success.

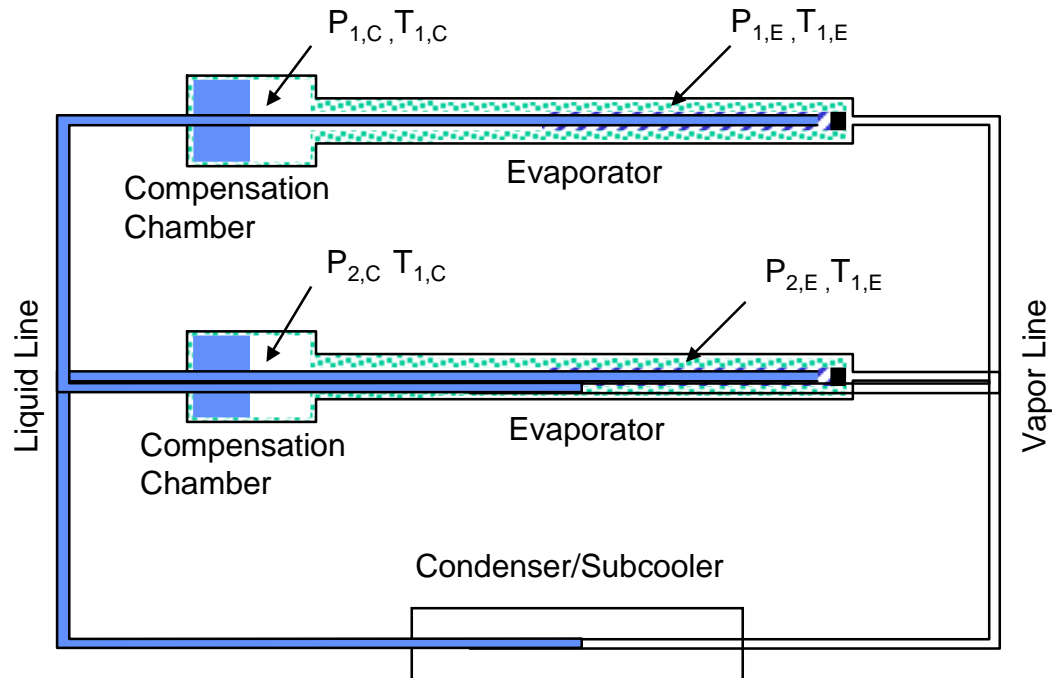
LHP Shutdown

- Some instrument operation requires LHP to shutdown for a period of time.
- LHP can continue to pump fluid if the evaporator temperature is higher than the CC temperature.
- LHP can not be shut down by simply applying power to liquid line as in a CPL.
 - Evaporator is vapor tolerant.
- Requirements for LHP shutdown
 - No net heat load to evaporator
 - CC temperature is higher than evaporator temperature
 - » Heating the CC is the only viable method
- Once the loop deprimed, fluid flow stops as long as there is no net heat load to evaporator.

LHP with Multiple Evaporators And Multiple Condensers

- **LHP with multiple evaporators and condensers**
 - Increased heat transport capability
 - Reduced temperature gradients of heat source
 - Multiple heat sources
 - Heat load sharing among evaporators
 - Multiple radiators
 - Flexibility in design and operation
- **Multiple condensers**
 - Flow regulators are desirable.
 - May yield multiple temperature hystereses
 - » Flow regulators will not eliminate hystereses
- **Multiple evaporator LHP configurations**
 - A common CC for all evaporators
 - » Limited capillary pressure head of secondary wicks
 - » Evaporators need to be close to one another
 - Parallel evaporators, each has its own integral CC

Multiple Evaporator LHP



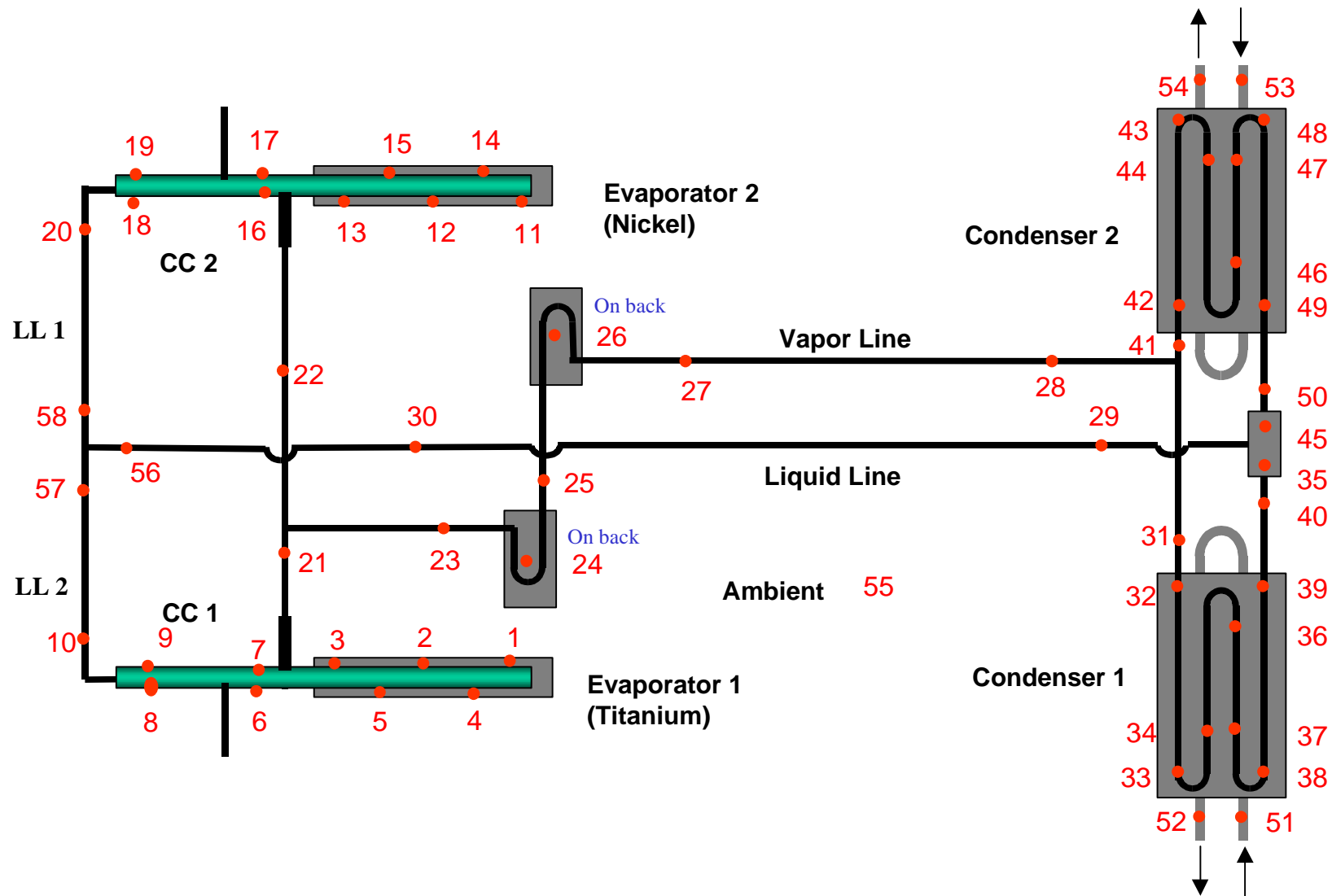
$$P_{1,E} - P_{1,C} = (dP/dT) (T_{1,E} - T_{1,C})$$

$$P_{2,E} - P_{2,C} = (dP/dT) (T_{2,E} - T_{2,C})$$

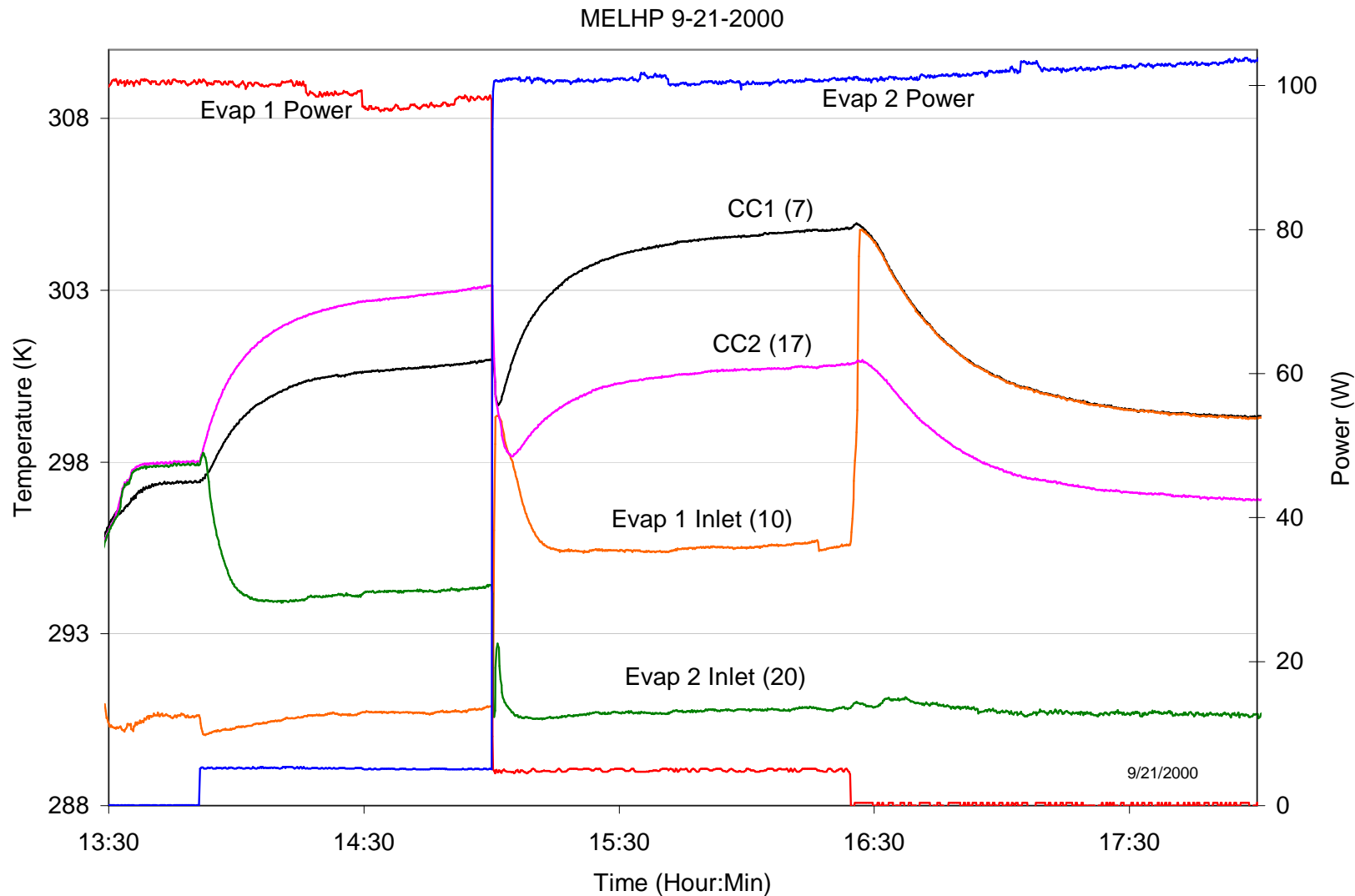
$$P_{1,C} - P_{2,C} = (dP/dT) (T_{1,C} - T_{2,C})$$

$$P_{1,E} - P_{2,E} = (dP/dT) (T_{1,E} - T_{2,E})$$

MELHP Test Set-up



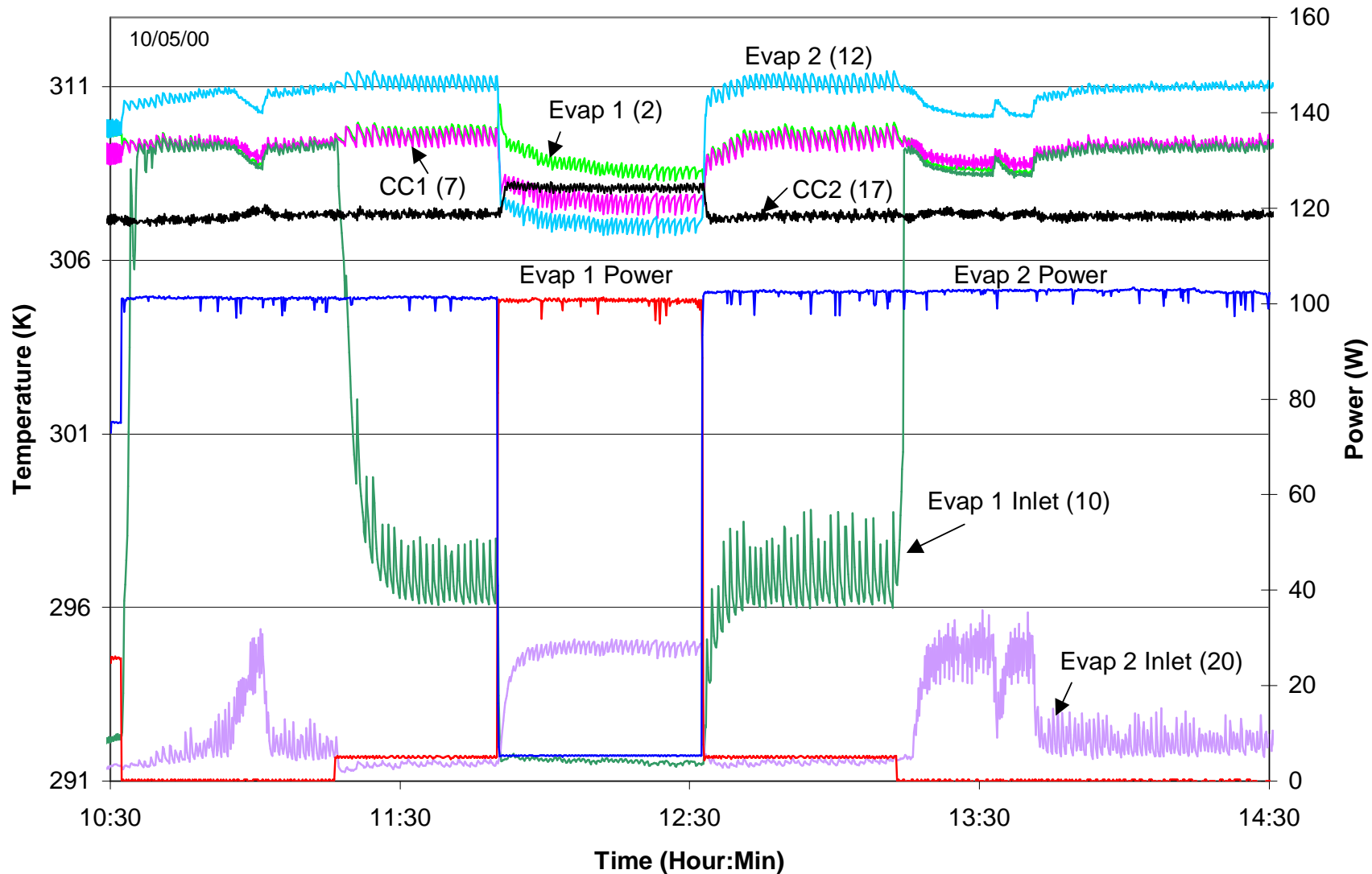
MELHP Power Cycle Test - Loop Temperatures (C1/C2 Sinks at 273K/273K)



MELHP Power Cycle Test - Loop Temperatures

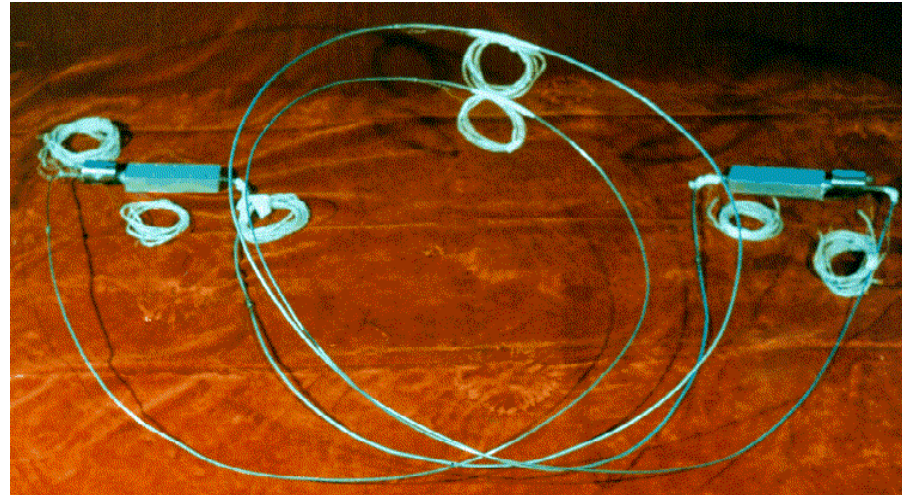
(CC1/CC2 Control Set at 308K, C1/C2 Sinks at 263K/258K)

MELHP 10-5-2000

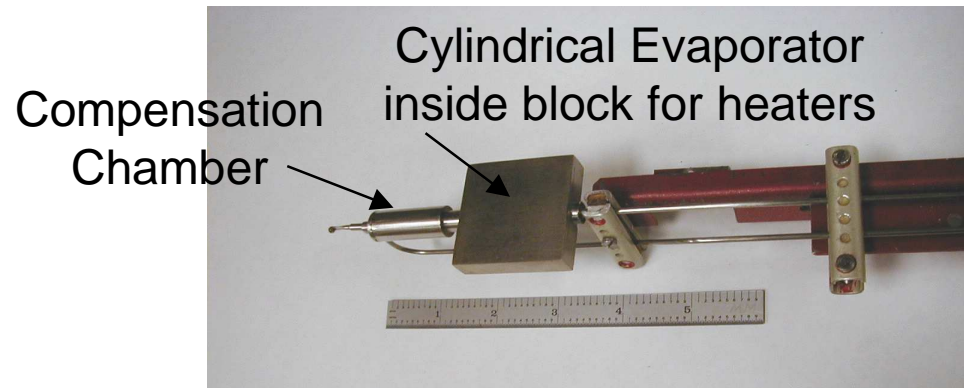


Miniature Loop Heat Pipes

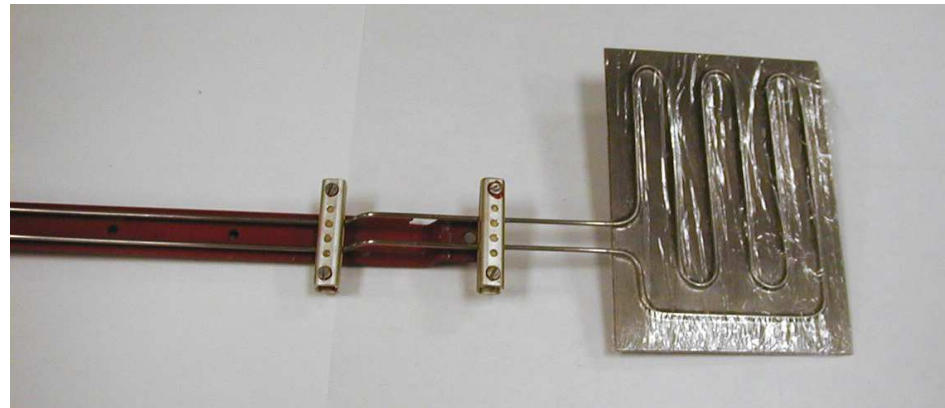
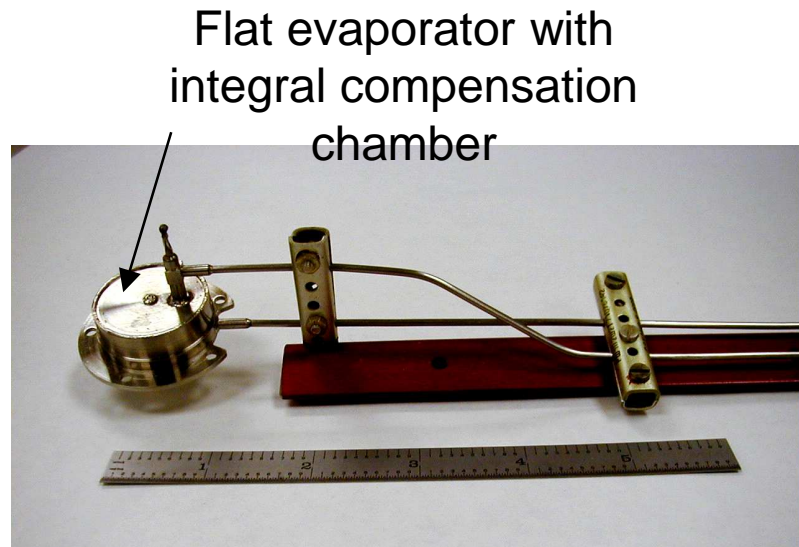
- Traditional LHP evaporators have 25.4mm diameter evaporators
- Evaporators with 13mm diameter have been made in last few years with excellent performance.
- Current goal is to develop evaporators with 6.35mm diameter.
- GSFC currently has three parallel development programs.
 - Joint effort with Air Force Lab (AFRL) to test 2 mini-LHPs manufactured by Russians - to be flown with CCQ Flight Experiment.
 - SBIR 2 program with contract to TTH Research Inc. - completed 3/03.
 - 3 year CETDP program started in 12/2000 - “Miniature Heat Transport System for Spacecraft Thermal Control”



Mini LHP for CCQ Flight Experiment

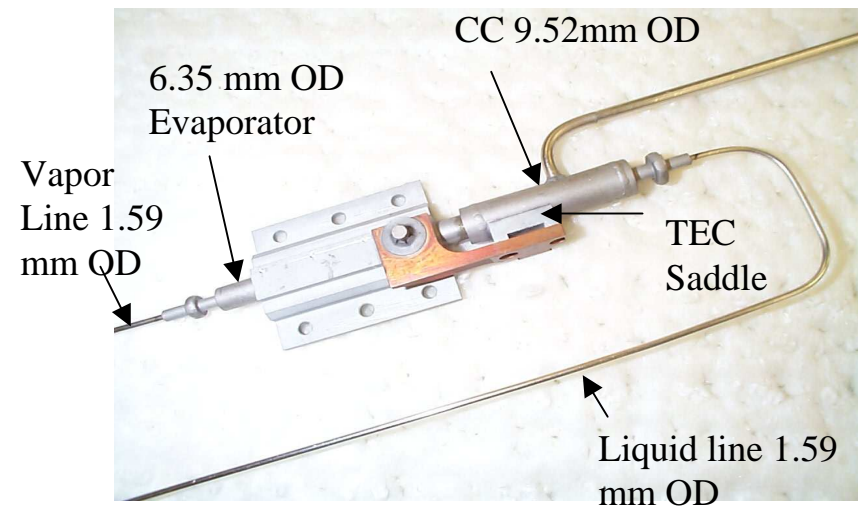
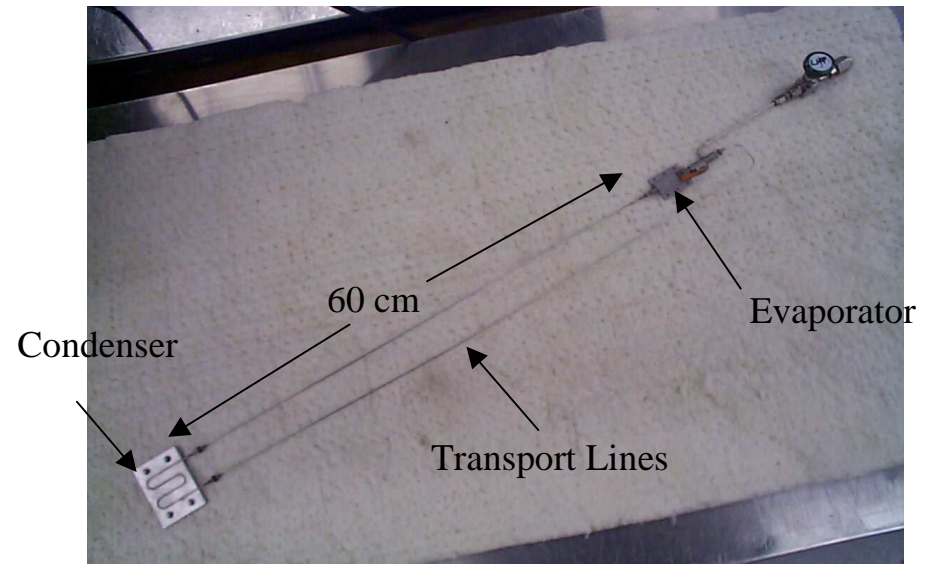
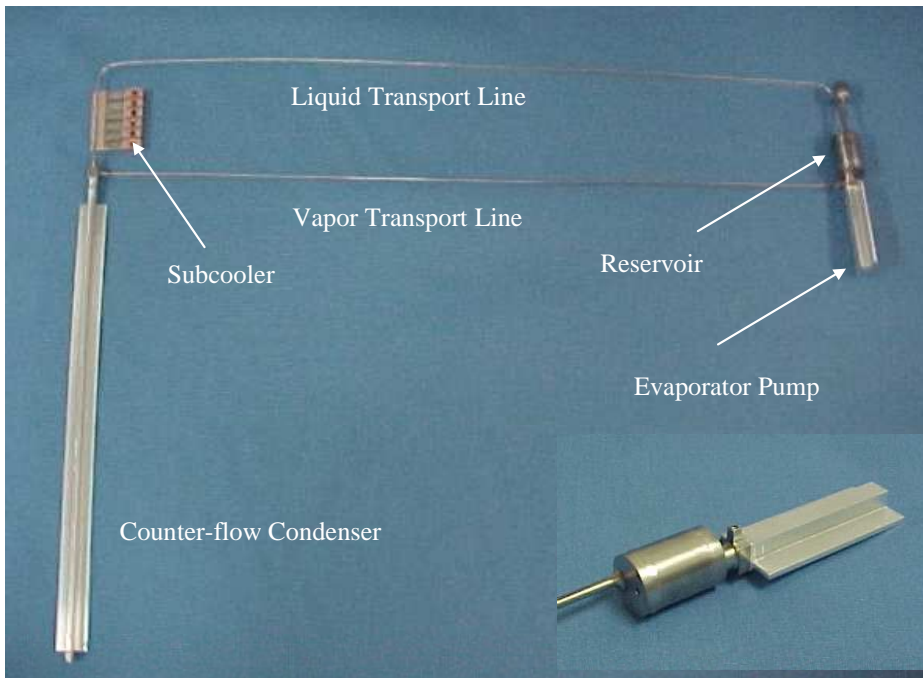


- Made by Russians
- To be flown for CCQ Flight Experiment in 2004(?)

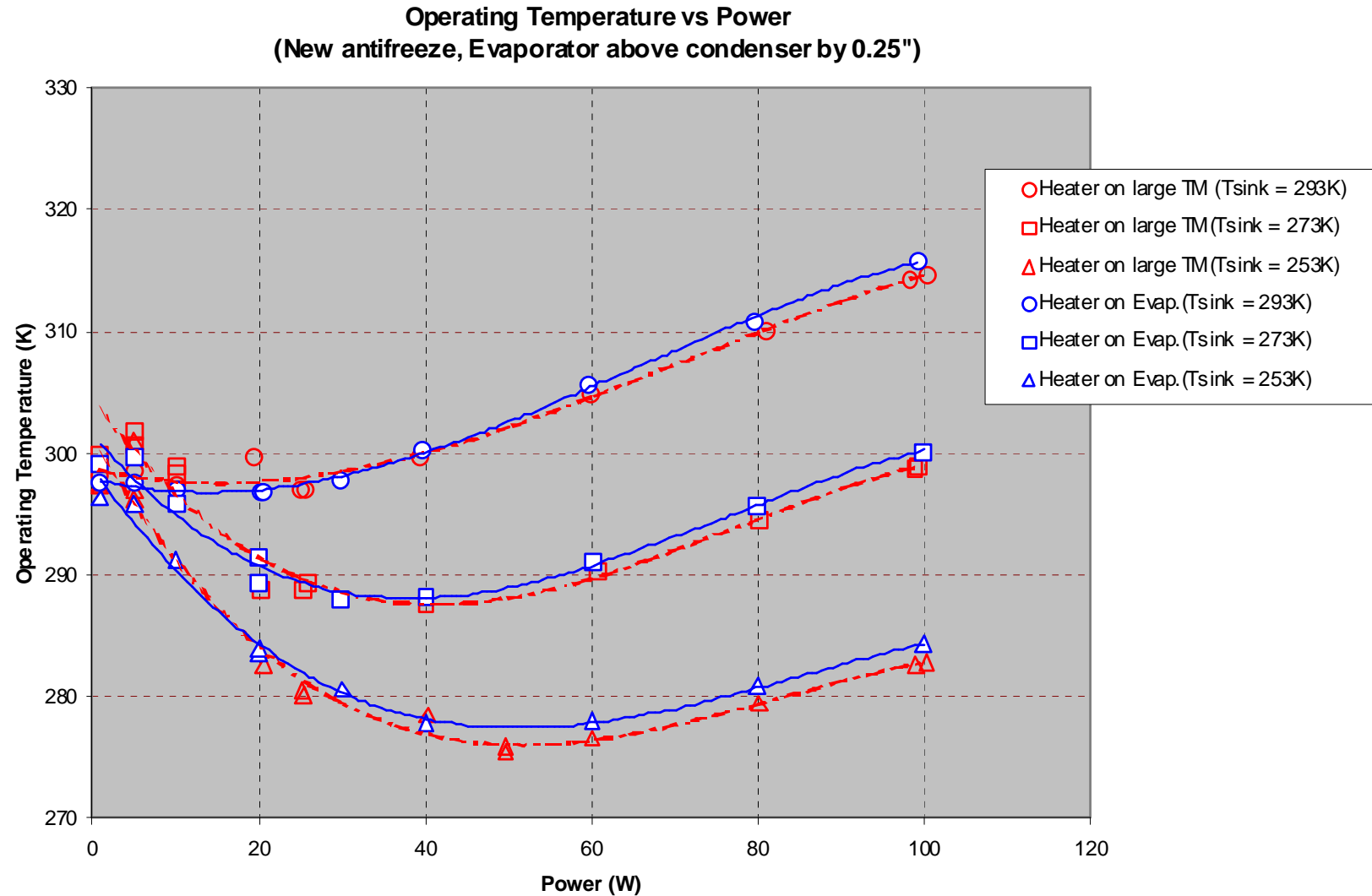


CEDTP Miniature Loop Heat Pipes

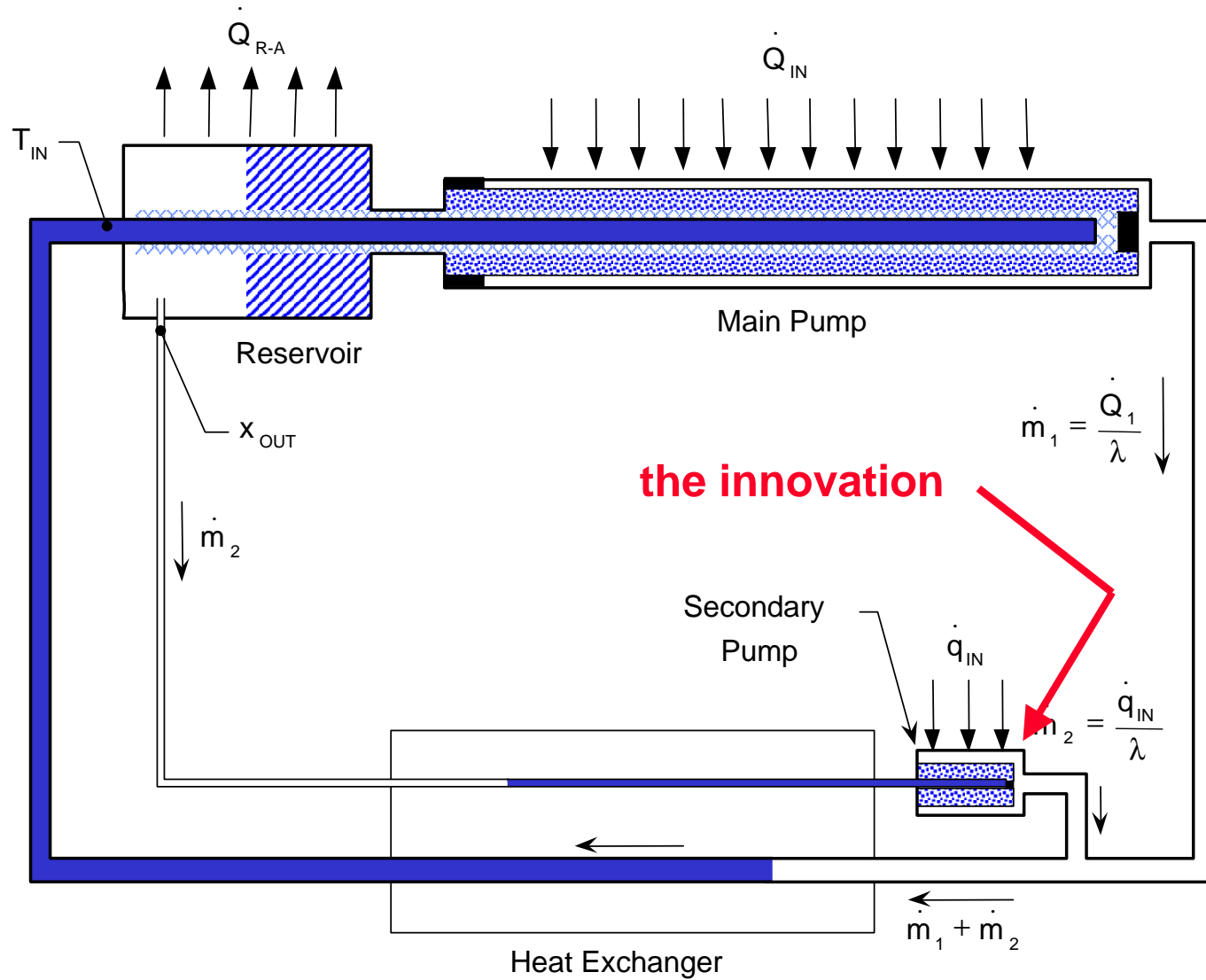
- **Miniature LHPs under the CETDP program.**
 - **Breadboards built by Swales and Thermacore**



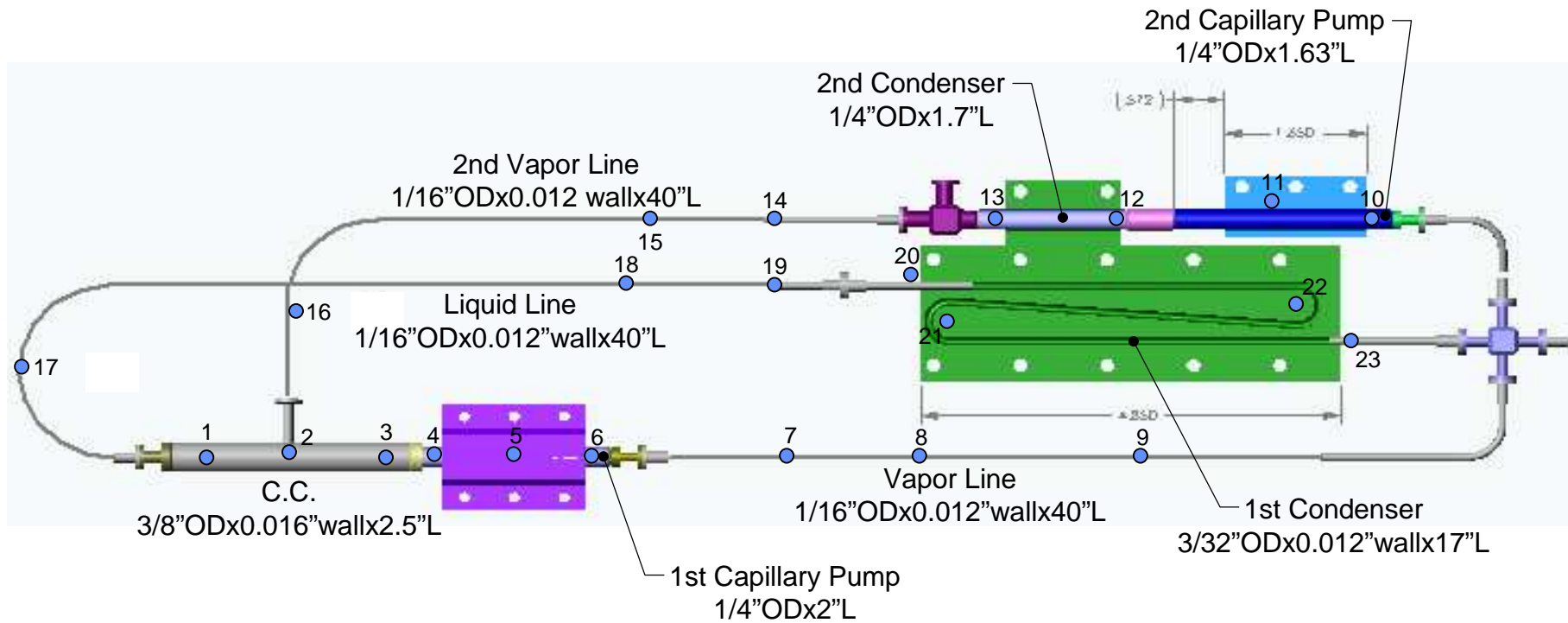
Ground Test Results of Thermoacore miniLHP



Advanced LHP



TTH Miniature LHP - SBIR 2



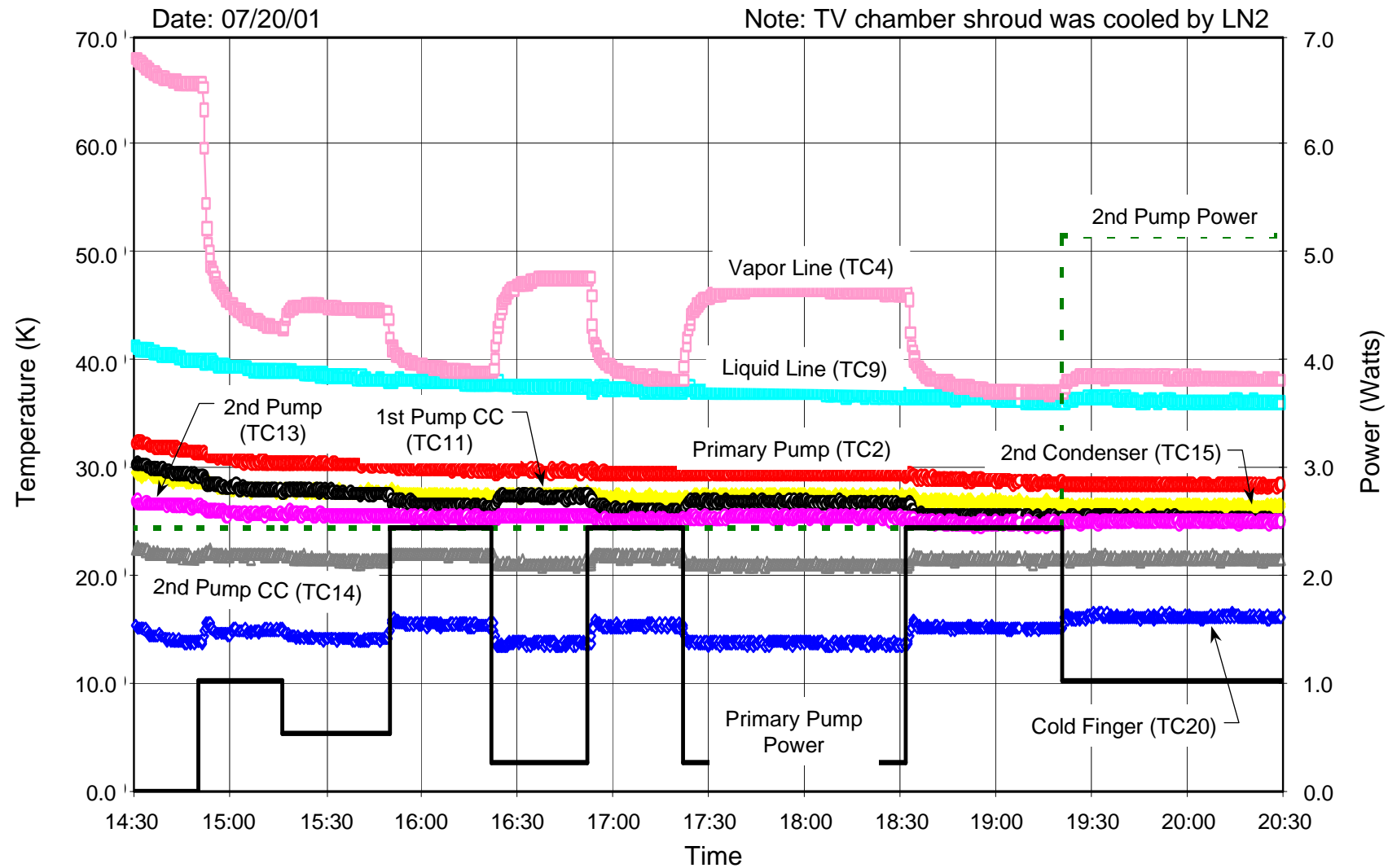
Cryogenic LHPs

- **Nitrogen LHP**
 - TTH/Thermacore - SBIR 2 (DOD)
 - 75K-100K
- **Hydrogen LHP**
 - TTH/Thermacore - SBIR 2 (NASA)
 - 20-24K, 2.5W
- **Neon LHP**
 - TTH/Thermacore -SBIR 1 (NASA)
 - 30K-35K, 4W
- **Helium LHP**
 - Proposed for SBIR 2 (NASA)
 - 4K, 0.5W

Hydrogen LHP Test

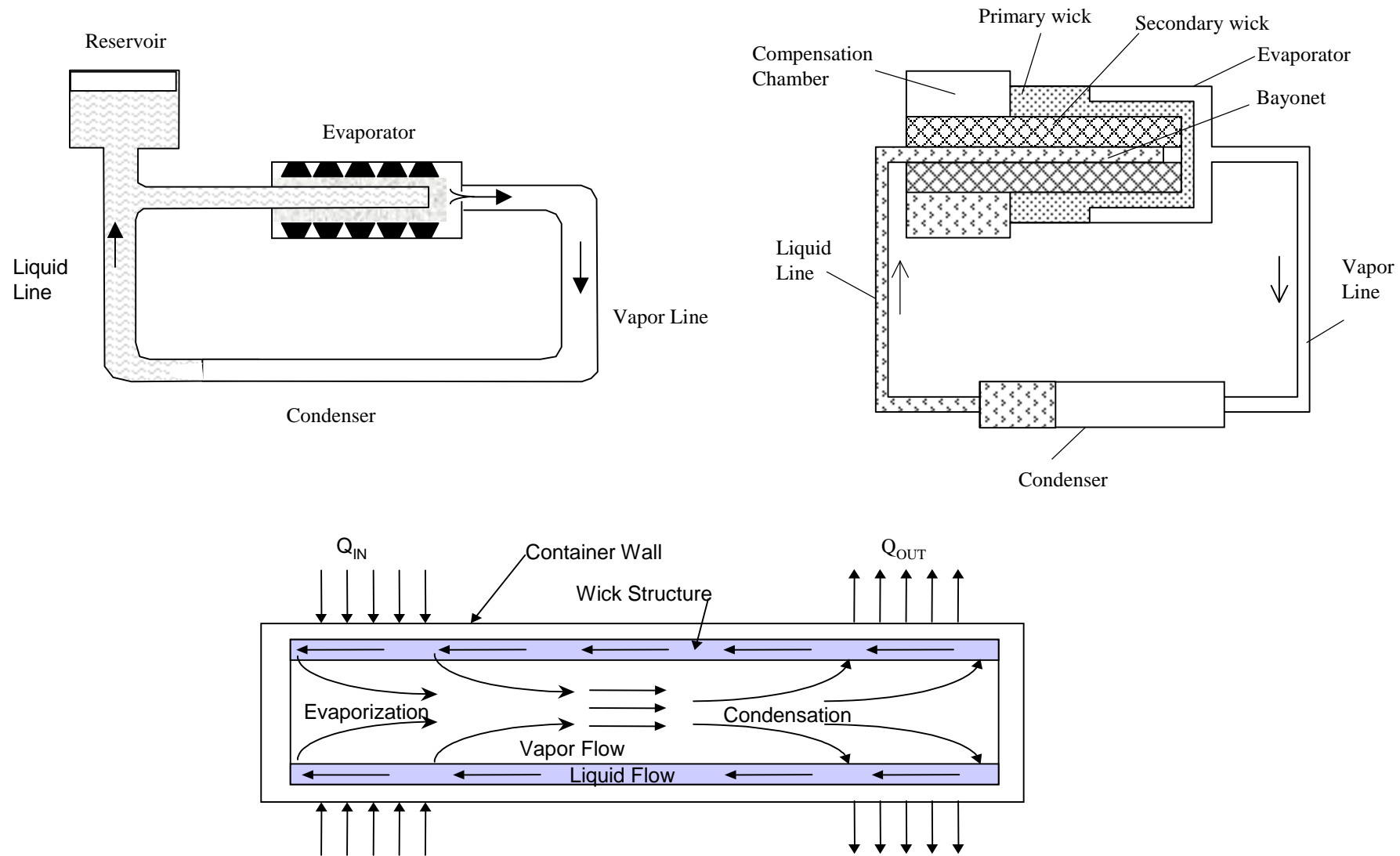


Hydrogen LHP Test Results



Summary

Developments of Capillary Two-Phase Thermal Devices



CPL Characteristics

(1 of 2)

- **Pre-conditioning of the loop is required in order to flood the loop prior to start-up.**
- **CPLs can not tolerate vapor bubbles in the evaporator core; need subcooling at all times.**
- **Current polyethylene wick has limited pumping capability.**
 - **Pore sizes around 20 microns**
 - **3500Pa pumping head using ammonia**
 - **About 0.5 meter against gravity**
- **The reservoir provides very precise temperature control, regardless of heat load and sink temperature.**
 - **Outside the path of fluid flow - saturation temperature is unaffected (little affected) by the loop operating condition.**
 - **The “master” that controls the loop temperature.**
 - **All transients are short-lived.**

CPL Characteristics

(2 of 2)

- **Power required to maintain reservoir temperature is small and independent of (insensitive to) the heat load.**
- **Reservoir can be located remotely from the evaporator.**
 - **Design flexibility**
- **Loops with multiple evaporators and multiple condensers have been demonstrated.**
- **Loops can be easily modified with reservoir re-sizing.**
 - **Evaporators are interchangeable between loops.**
 - **Transport lines and condensers can be changed.**
- **Loops are either functional or deprimed, no graceful degradation.**
 - **Needs re-start once deprimed.**

LHP Characteristics

(I of 2)

- **Loops are very vapor tolerant, and provide robust operation.**
- **Metal wicks with pore size of about 1 micron provides high pumping capability.**
 - **35KPa using ammonia**
 - **Over 4 meters against gravity**
- **The CC temperature is a function of heat load, sink temperature, ambient temperature, and pressure drop.**
 - **The CC is located along the path of the fluid flow).**
 - **The CC is only a “semi-master”.**
- **The vapor void fraction inside the evaporator is a key factor in determining the loop operating temperature.**
 - **A “black box” which can not be controlled by the operator.**

LHP Characteristics

(2 of 2)

- **Temperature hysteresis has been observed in most existing loops.**
- **The operating temperature can be controlled. The heater power is dependent upon the heat load and sink temperature, and can be very large.**
- **In heat load sharing mode of operation, the operating temperature will be higher than the ambient temperature regardless of heat load and the sink temperature.**
- **Loops provide graceful degradation instead of complete deprime.**
- **Each evaporator/CC is uniquely designed for a given loop.**
 - **Usually not interchangeable among different loops**
 - **Very limited design flexibility**
- **Loops with multiple evaporators have been demonstrated.**
 - **Two or three evaporators seem to be the limit.**

Selecting a Capillary Two-Phase Thermal Design

1 of 2

- It is the thermal engineer's responsibility to select the simplest and safest system that will suffice.
- Select traditional passive thermal designs if possible.
- Select CCHPs if possible.
- Selection of CPL or LHP may be compelling if not enabling.
- Certain mission-specific requirements may dictate the selection of CPL or LHP.
 - Both CPL and LHP have tremendous design flexibility.
- Use LHPs if
 - Temperature control is not too restrictive.
 - Real estate is not an issue in the evaporator vicinity.
 - Frequent start-up and shut-down during the mission is expected.
 - Significant thermal design is not expected as the project moves along.
 - Large body forces are expected during the mission.

Selecting a Capillary Two-Phase Thermal Design

2 of 2

- **Use CPLs if**
 - **Infrequent start-up and shut-down are expected during mission operation.**
 - **Very tight temperature control is required.**
 - **Large uncertainties in thermal design exist in the early phases of project.**
 - » **Possible future growth of radiator size and/or transport line length**
 - » **Possible future growth in number of evaporators**

Analytical Modeling

- **HP Models**
 - **GAP for CCHPs**
 - **VCHP**
 - **SINDA/Fluint**
 - **CPL Models**
 - **SINDA**
 - **SINSA/Fluint**
 - **LHP Models**
 - **Several institutions have developed steady state models.**
 - » **Based on concurrent pressure and energy balances at each element**
 - » **Spread sheet format**
 - **LHP transient model**
 - » **Difficult due to complex physical processes**
 - » **Some models exist**
 - » **Utilize other thermal analyzers to provide boundary conditions**
 - » **SBIR 2 program on-going**
 - **Dimensionless Groups**
-

Simplified LHP Thermal Network

